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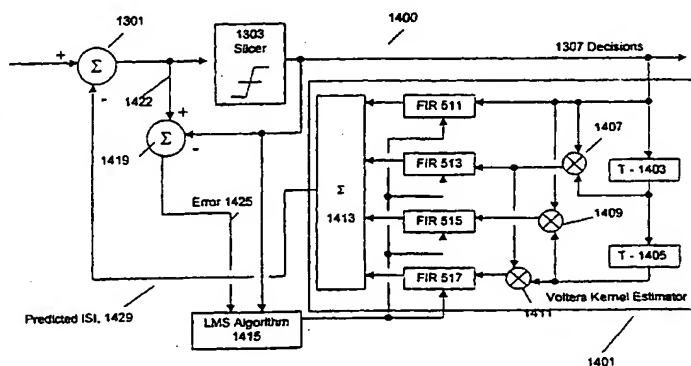
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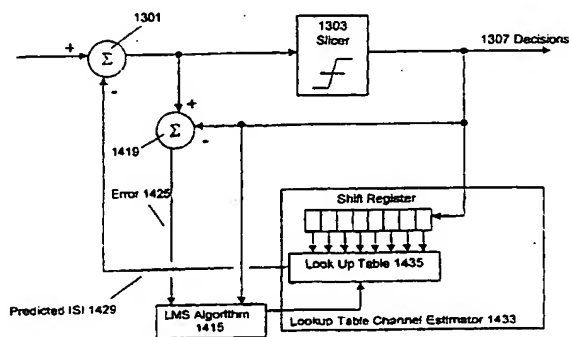
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**(54) Title:** METHOD AND SYSTEM TO IDENTIFY AND CHARACTERIZE NONLINEARITIES IN OPTICAL COMMUNICATIONS CHANNELS



**(57) Abstract:** A method for identifying and modeling nonlinearities in communications channels, particularly optical communication channels. A channel in general is modeled as a summation of linear and non linear terms having memory. The terms are functions of the input to the channel with respect to time, such as a sequence of input bits to the channel. In one embodiment the most recent 5 input bits to the optical channel are used to access a value in a look up tale. The value accessed is then compared to an actual value received from the channel. The difference between the value in the table and the actual channel value may be used to correct the value in the table, for example using a LMS (Least Means Squared) algorithm. When the look up table and the channel converge the look up table contains a model of the channel with memory that can model nonlinearities. A nonlinear channel having memory may also be modeled in terms of Volterra Kernels, which may equivalently change into a look up table odel using the Hadamard transform. The Volterra Kernel representation also has the added advantage that it can represent a look up table of N table entries in at most N-1 Volterra kernels. In many cases only a few Volterra Kernels are required to model the behavior of the channel. For example embodiments are disclosed in which two Kernels may model a nonlinear fiber optic channel, operating at a wavelength of 850 nanometer through a multimode channel at a data rate of 1 Gigabit per second.





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# METHOD AND SYSTEM TO IDENTIFY AND CHARACTERIZE NONLINEARITIES IN OPTICAL COMMUNICATIONS CHANNELS

## FIELD OF THE INVENTION

The invention relates to methods used to characterize communication channels and, in particular embodiments, to methods used to characterize and model nonlinear optical communication channels.

## BACKGROUND OF THE INVENTION

Signal distortion in an optical channel may be caused by nonlinearities that exist in various components, which comprise an optical channel. Such distortion can be characterized by mathematical models of the nonlinear behavior of the optical communication channel. By using such models, compensatory measures, for example equalizers that compensate for distortion, which degrades the performance of the channel, may be designed.

One source of distortion is dispersion. Dispersion may be a combination of linear and nonlinear components.

Dispersion found in optical fibers, particularly multimode fibers, may limit the bandwidth in optical channels. The problem of dispersion may be more acute in multimode fibers in general, but it may also be a problem in single mode fibers, especially in long runs of fiber. Single mode fibers commonly have lower dispersion than multimode fiber. The dispersion commonly found in single mode fibers may be chromatic dispersion or polarization mode dispersion. The dispersion that is seen in single mode fibers is generally a lot less per length than the dispersion found in multimode fibers. Dispersion is cumulative, however, and so tends to increase as fibers increase in length. Accordingly, methods discussed herein in terms of multimode fibers may apply equally well to single mode fibers.

In multi-mode fibers, the multiple modes of propagation within the fiber commonly cause dispersion. Generally, in the various modes of propagation within a fiber, the light signal has different speeds of propagation. So if a light pulse is sent from a transmitter, the pulse will propagate in multiple modes traveling at different speeds. The pulse, traveling in each mode, will reach the receiver at a different time. The multiple times of arrival of the input pulse traveling in several modes create a distorted pulse, somewhat like a spread out version of the transmitted pulse.

Optical channels are inherently nonlinear. Electromagnetic fields can be described by Maxwell's equations, which are linear. Because Maxwell's equations are

1 linear, the principle of superposition applies to the electromagnetic field. What is  
modulated, however, in optical channels is not the electromagnetic field per se, it is the  
optical power. Superposition doesn't exactly apply to optical power.

5 An optical photo detector is commonly a square law device. The photodetector  
responds linearly to the optical power, in fact the photo current generated by a  
photodetector is commonly a very accurately linear function of the optical power, but the  
power is a quadratic function of the electromagnetic field, thus creating a source of  
nonlinearity.

10 It has been shown that if a laser has a large spectral width, instead of being a  
very monochromatic laser, the significant spectral width tends to result in a linearization  
of the channel even considering the effect of the optical power and the square law  
nature of the photodetector. In other words if a laser has a very monochromatic, narrow  
spectrum then the channel tends to behave less linearly than does a laser that has a  
wider spectrum.

15 Nonlinear behavior in an optical channel may depend to varying extent on the  
properties of the photodetector and the fiber. Additionally there is a possibility of  
distortion from the laser itself. If there is dispersion in the laser, for example because  
the laser has some bandwidth limitation itself, then nonlinearity of the laser could also  
contribute to the total nonlinearity in the optical channel.

20 When the intensity of an optical signal is high, a fiber optic which transmits the  
optical signal itself may introduce nonlinearities. These nonlinearities may result from  
the fact that the index of refraction of the fiber optic depends, to some extent, on the  
intensity of the optical signal itself. This effect commonly gives rise to nonlinearities  
known as "four-wave mixing", "self-phase modulation", and "cross-phase modulation".  
25 Additional nonlinearities may result from the phenomena known as stimulated Raman  
scattering and stimulated Brillouin scattering. For a more comprehensive treatment of  
nonlinearities, see the text "Fiber-Optic Communication Systems", second edition, by  
Govind P. Agrawal, John Wiley and Sons, 1997, ISBN 0-471-17540-4, which is  
incorporated by reference herein.

30 Although the above sources of nonlinearity in an optical channel are presented  
as examples, other sources may exist. The techniques described in this disclosure may  
be applied to all kinds of nonlinearities regardless of their physical source, as will be  
clear to those skilled in the art.

## 35 SUMMARY OF EMBODIMENTS OF THE INVENTION

In one aspect of the invention, the disclosure illustrates a method for modeling



1 the behavior of a data channel. To create the model, the sequence of data input to the data channel is examined. A portion of the sequence of data input to the data channel is used as an index to a channel model value. Output data from the channel is sampled. A numerical channel model value is compared with the sampled value and  
5 the channel model value is adjusted based on the results of the comparison.

In another aspect of the invention, a method for modeling the behavior of a data channel using Volterra Kernels is illustrated. A sequence of data is provided to the data channel. A part of the sequence of data input to the channel is provided to the Volterra Kernel model of the channel. The Volterra Kernel (VK) model produces a channel  
10 model value. The data values measured from the channel are compared to the VK channel model value and the results used to update the Volterra Kernel model.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The features, aspects, and advantages of the present invention, which have been  
15 described in the above summary, will be better understood with regard to the following description, appended claims, and accompanying drawings where:

Figure 1 is a graphical illustration of an environment in which embodiments of the present invention may be used.

Figure 2 is a graphical illustration of an equipment setup, which may be used to  
20 characterize optical channels.

Figure 3 is a table listing of fibers, which were measured using the measurement setup illustrated in figure 2.

Figure 4 is a graphic illustration of an example of a system that may be used for channel identification.

Figure 5 is a graphical illustration of channel identification based on Volterra  
25 Kernels (VK).

Figure 6 is a graph illustrating measurement of a channel having an 850 nanometer VCSEL (Vertical Cavity Surface Emitting Laser) and fiber F0, and comparing the signal measurements to linear and nonlinear channel models.

Figure 7 is a graph illustrating the measurement of a channel having an 850  
30 nanometer VCSEL and fiber F0, and comparing the amount of error generated by linear and nonlinear channel models.

Figure 8 is a graph representing an impulse response and a second order Volterra Kernel for an 850 nanometer VCSEL and fiber F0.

Figure 9 is a table of the signal to noise ratios computed for linear and nonlinear  
35 channel models for a channel operated at a wavelength of 850 nanometers.

1           Figure 10 is a graph comparing linear model, measured signal and error within a channel using a fiber F0 at a wavelength of 1310 nanometers.

          Figure 11 is a graph of the impulse response and a second order Volterra Kernel for a channel using fiber F0 and a distributed feedback (DFB) laser with 1310  
5   nanometer wavelength.

          Figure 12 is a table of signal-to-noise ratios for a linear model of a channel employing 1310 nanometer DFB laser.

          Figure 13 is a block diagram of a nonlinear optical channel equalizer, according to an embodiment of the invention.

10          Figure 14A is a block diagram of a nonlinear optical channel equalizer that employs a Volterra Kernel estimator according to an embodiment of the invention.

          Figure 14B is a block diagram of a non-linear optical channel equalizer employing a lookup table channel estimator, according to an embodiment of the invention.

          Figure 15 is a Viterbi decoder employing a nonlinear channel estimator, according  
15   to an embodiment of the invention.

#### DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

          The listed figures describe and illustrate various aspects of the present invention.

          Accordingly, Figure 1 is a graphic illustration of an environment in which  
20   embodiments of the present invention may be used. The environment illustrated at 101 is an information distribution system, such as may be found, for example, in a computer network accessing a remote database.

          In Figure 1, users 105 are coupled to a server 103. The users then may communicate with remote database 107 using fiber optic 109. Fiber optics may be  
25   used to communicate large amounts of data between points because of their large bandwidth.

          The data rate of optical channels is, in part, limited by nonlinearities in the channel. The term "channel", as used herein, includes the laser, amplifiers that drive the laser, the fiber optic, the photo detector receiver and all elements included in the  
30   transmission and reception of a fiber optic signal.

          For characterizing optical channels, the measurement setup illustrated in Figure 2 was used.

          Figure 2 is a graphical illustration of an equipment setup used to characterize optical channels. A signal is generated by modulating a laser 219. The modulated  
35   laser signal is provided to a fiber optic 215. In the embodiment illustrated in Figure 2, the signal provided to the optical channel was a 1 Gigahertz (GHz), 127 bit, pseudo-

1 random binary sequence provided by bit error rate tester 201. The resulting received  
signal was detected by a photodetector 207, captured using an oscilloscope 205 and  
stored as a file in computer 209. Using computer 209, the received signal may be  
processed and the nonlinearity that exists in the received signal can be identified. The  
5 approach taken is that no attempt is made to identify the source of the nonlinearity as  
belonging to a specific channel component such as a photodetector or laser or any  
other source. Instead the nonlinearity in the received signal was examined without  
being concerned for the physical source of the nonlinearity.

Two types of lasers were tested. The first type was a 850 nanometer VCSEL  
10 (vertical cavity surface emitting laser) and the second type of laser was a 1310  
nanometer DFB (distributed feedback) laser. All measurements were done at a data  
rate of 1 gigabit per second.

The bit error rate data tester 201 generated a pseudo random binary sequence  
that was periodically repeated. The channel measurements were performed at a data  
15 rate of 1 gigabit per second, but the method may be applied to any data rate.

In the setup illustrated in Figure 2 free space optics and an optical bench 221  
were used. The laser was aligned using alignment screws so that the laser 219, the  
fiber 215 and the lens were arranged to focus the light into fiber 215. Laser 219  
requires a DC bias current provided by bias power supply 203. A bias Tee 211 allows  
20 the combination of the data signal with a bias in order to apply a correctly biased data  
signal to the laser 219.

A length of fiber 215 is contained in a spool so that lengthy fibers up to more than  
1 kilometer may be used. In the case of single-mode fibers, the length of the spool  
could exceed 700 km. Photodetector 209 is a commercial unit having a bandwidth of  
25 10 gigahertz. The oscilloscope 205 is a real time sampling oscilloscope which samples  
at 8 gigahertz. Because the data rate used was 1 gigabit per second, the received  
signal was sampled on average 8 times per bit. Samples of the received signal were  
captured in the memory of the oscilloscope and then downloaded to the computer 209  
in the form of a file. Typical received signal data files contained about 65,000 data  
30 points representing received samples of the pseudo random input sequences of 127  
bits.

Once the data points have been accumulated they may be processed and  
information about the behavior of the optical channel, particularly the nonlinearity, may  
be extracted. Additionally any possible nonstationarity of the channel may be identified.  
35 In other words, if the channel changes in time, such nonstationarity may be detected.  
In the measurements taken, however, no significant nonstationarity was observed.

1           Figure 3 is a table listing of fibers, which were measured using the measurement  
setup illustrated in figure 2. Six different fibers, having core diameters from 50 to 62-1/2  
microns and the lengths from 270 meters to about 2.2 kilometers, were tested. All of  
5           the fibers exhibit some dispersion phenomenon and bandwidth limitation to varying  
extent.

To model channel nonlinearity two different mathematical methods, representing  
nonlinear functions having memory, were chosen. Because dispersion is inherently  
a function having memory, the resulting channel nonlinearity is a nonlinear function with  
memory, as opposed to memoryless nonlinearity. Memoryless nonlinearity may be  
10          represented by a function of the form  $Y = F(X)$ , with the nonlinearity an arbitrary  
nonlinear function  $F$  of a single variable. Nonlinearity with memory can be described  
as a nonlinear function of a number of consecutive samples of the transmitted data, so  
that the nonlinear function with memory is of the form  $Y = F(X_n, X_{n-1}, X_{n-2}, \dots)$ . In other  
words nonlinearity with memory is a function of several variables, where the variables  
15          are exemplarily samples of the transmitted bit sequence. Nonlinearity with memory is  
a more general kind of nonlinearity that may be found in optical channels. In other  
words the characteristic of an optical channel is not only a function of the current bit, but  
depends also on previously transmitted bits.

The nonlinearity in an optical channel can be modeled as a look-up table, for  
20          example as a nonlinear function of the five most recently transmitted bits. In a digital  
transmission system the transmitted bits have 2 levels, 0 and 1 (or +1 and -1 depending  
on the convention that is used). Because of the discrete nature of the transmitted bits,  
the function characterizing a channel depending on the five most recent bits can only  
have  $2^5=32$  values. Accordingly there are 32 possible values that model the channel  
25          by listing all the values for all the possible sequences of the most recent 5 input bits.  
Such a model can be implemented as a look-up table. The look up table is one model  
with memory for characterizing an optical channel having nonlinearity.

A second optical channel model is based on a Volterra series. Volterra series  
have been studied in mathematics for a considerable time. Volterra series are a way  
30          to represent nonlinear functions. In general Volterra series are infinite series, i.e. a  
series with infinite number of terms. In the present case, however, since the transmitted  
data is binary, the number of terms is finite. The number of terms in the series used to  
model a binary optical channel is 2 to the power  $N$ , where  $N$  is the number of most  
recent transmitted bits, which are taken into account. That is the same number of terms  
35          as the number of entries in a look-up table. Accordingly, no matter what description is  
used, whether the look-up table approach or the Volterra series approach, the number

1 of required elements in each model is 2 to the power N, where N is the number of most recent bits transmitted that are taken into account. In the look-up table approach the 2 to the N parameters are the values of the channel for all the possible values of the most recent N input bits.

5 For the Volterra series, the parameters are the coefficients of the series and because the series has  $2^N$  terms there are  $2^N$  coefficients.  $2^N$  is the same number of parameters as required by the look up table model. Accordingly regardless of which description is chosen, the maximum number of parameters that is needed to completely specify the nonlinear function is the same, i.e.  $2^N$ . It can be shown that the Volterra  
10 Kernel representation is mathematically equivalent to the look-up table. In fact a mathematical transformation known as the Hadamard transformation can transform the look up table model to the Volterra Kernel model and Volterra Kernel model to the look up table model.

15 N is generally an empirically determined value, the exemplary value of  $N=5$  in the present embodiment appears to work very well. The value of N, of course could depend on the fibers, wavelength of the laser and the rate of the data being transmitted. In principle it is possible to find fibers where N is larger or smaller, but in present embodiments  $N=5$  is sufficient.

20 An advantage of choosing the Volterra series description is that there is a way to make the description somewhat compact by grouping terms. By grouping the terms  $2^N$  terms are transformed into  $2^{(N-1)}$  convolution-like terms having a shift register-type sequence. That means, for example, the terms that go into the sequence of grouped terms are products of bits. So, for example, a  $X_N$  term would be multiplied by an  $X_{N-1}$  term and so on. The shift register sequence of grouped terms means shifted versions  
25 of the product. So, for example, this shift register sequence would be in the form  $X_N * X_{N-1}$ ,  $X_{N-1} * X_{N-2}$ ,  $X_{N-2} * X_{N-3}$  and so on. This is shift register-type sequence is one that can describe terms of the Volterra series as a convolution of this kind of shift register-type sequence with a certain kernel. A kernel is an element that resembles an impulse response. A kernel is not an impulse response in the traditional sense, but a traditional  
30 impulse response is used as a linear portion of the nonlinear kernel function.

Terms involving a convolution of a shift register type sequence with a certain kernel, are referred to as Volterra Kernels. There are multiple Volterra Kernels corresponding to different kinds of products of bits. The maximum number of Volterra Kernels needed to represent an N bit sequence to is  $2^{N-1}$ . So, for example, in the case  
35 where  $N=5$ , the total number of terms in the Volterra series is  $2^N$  or 32 terms. But these 32 terms can be mapped into 16 Volterra Kernels. Sixteen Volterra Kernels suffice and

1 the number of Volterra Kernels is equal to  $2^{(N-1)}$ , or in the present example  $2^4$  or 16. So  
there are 16 Volterra Kernels and the Volterra Kernels may provide a more convenient  
and more compact description of a nonlinearity particularly because commonly in many  
applications the number of Volterra Kernels is actually less than  $2^{(N-1)}$ . Although the  
5 number of Volterra Kernels to theoretically define a Volterra Kernel model is  $2^{(N-1)}$ , some  
of the kernels are very small and can be neglected. In some situations the channel may  
be effectively modeled by one or two Volterra Kernels. That is the situation in the  
optical channels of the present embodiment. In present embodiments the nonlinearity  
is simple enough so that it can be described completely by a linear term and a single  
10 Volterra Kernel, indicating that a fairly simple kind of nonlinearity is present.

Because the nonlinearity is simple doesn't mean that its negligible. In fact in  
present embodiments the nonlinearity, though simple, is a very strong. Because the  
nonlinearity has a simple description, simple equalizers may be built. In other words  
nonlinear equalizers with memory which are relatively simple but very powerful may be  
15 built. Such equalizers can be very effective because they can deal with the nonlinearity  
that is strong whereas a traditional kind of linear equalizer might fail completely.

Figure 4 is a graphic illustration of an example of a system that may be used for  
channel identification. The system is implemented in software.

20 Input bits 401 are provided to a channel 403. What is used for the channel 403  
is the measurements that were taken with the setup illustrated in Figure 2. So the  
channel input and channel response are actual measured values.

In the present embodiment the measurements are stored in a file and then  
processed off-line in a computer using a software program that implements the  
remainder of the system illustrated in Figure 4. This was done for the sake of  
25 convenience because the equipment for the setup in Figure 2 was readily available.  
There is however no constraint to prevent the present disclosed methods from being  
implemented as part of a real time or embedded system.

The look-up table 409 is adaptive. That is the value in it can be adapted using  
the LMS (least-means-squared) algorithm. Basically what is done is to compare the  
30 measured sequence from the channel 403 (the file of received values stored by  
computer 209) with the output of the look-up table. The addresses in the look up table  
409 are received from a shift register 407 representing the values of the latest 5 input  
bits provided as input to the channel. Initially the look-up table values are initialized to  
all zeros started from situations where there is no knowledge of the nonlinearity. In  
35 such a case the error will be equal to the input signal. So the error will be large initially.  
The values in the look up table can be adjusted using an LMS algorithm to update the

1 look-up table according to the error 405 observed. The LMS algorithm will converge so that it tends to drive the error to zero or as close as possible to zero.

Once the look-up table converges the error will be small or zero. In actual practice the error may not be exactly zero because the input signal may include some random noise. Additionally it is also possible the look-up table doesn't perfectly model all the nonlinearity. There may be some residual unaccounted for nonlinearity because N was chosen equal to 5 but in practice a N of 8 or 10 may have been required to more closely model the fiber. The choice of N is an implementation detail depending on the type of fiber, data rate, and a variety of other factors.

10 Additionally in figure 4 the look up table is like having an array where the address is created by looking at 5 consecutive bits, but the number is accessed is a single number that could be represented by multiple bits which could be 16 bits or 24 bits, and as such may contain some quantization error.

Figure 5 is a graphical example of channel identification based on Volterra Kernels. The Volterra Kernel approach is an approach mathematically equivalent to the use of a look-up table, as illustrated in Figure 4. In Figure 5, four Volterra Kernels are used. Normally there would be 16 Volterra Kernels present in a case where N is equal to 5. In some cases some of the Volterra Kernels may be negligible and depending on the Bit Error Rate (BER) required only the most important ones may need to be taken into account in the model, as for instance illustrated in Figure 5. For example in Figure 5 there is a linear term which is represented by the Kernel labeled FIR 511. "FIR" indicates that each Kernel is represented by a finite impulse response (FIR) filter. In Figure 5, FIR 511 directly takes a sequence of input bits and creates a convolution of the input sequence with an impulse response of FIR filter 511. Hence FIR 511 is a linear term, i.e. a traditional convolution. So if only a term represented by FIR 511 is needed for the channel model, the channel is essentially linear. If, in addition to FIR 511, other terms are present then the model is nonlinear.

FIR 513 is a Volterra Kernel which is associated with products of two consecutive bits, i.e. a second order Volterra Kernel. FIR 513 is a second order Volterra Kernel because it accepts a term 505 which is a product of the most recent input bit and the bit preceding the most recent input bit. The most recent input bit is designated as  $A_N$  and the bit preceding the most recent bit is designated  $A_{N-1}$ .

Second order Volterra Kernel FIR 513 is associated with two (consecutive) bits i.e. bits that are one time delay apart, it accepts the product of two (consecutive) bits. Another second order Volterra Kernel 515 is produced by taking the product of bits that are two time delays apart, 501 and 503 representing time delays. The most recent bit

1 and the bit prior to the second most recent bit are multiplied and result in output 507,  
which is the accepted by FIR 515. In other words  $A_N$  is multiplied by  $A_{N-2}$ , here, because  
this is delayed by 2 units. FIR 515 is a Finite Impulse Response filter (just as FIR 511  
and FIR 513) but the input, instead of being bits is the product of 2 bits, and so it is a  
5 second order Volterra Kernel. FIR 515 accepts the product of bits  $A_N$  and  $A_{N-2}$ , so it is  
a different type of Volterra Kernel than FIR 513 that accepts sequential bits. Both FIR  
515 and FIR 513 are second order.

A third order Volterra Kernel FIR 517 is determined by the product (509) of 3 bits.  
509 is a product of 3 consecutive bits  $A_N$ ,  $A_{N-1}$  and  $A_{N-2}$ . Accordingly FIR 517 is a third  
10 order Volterra Kernel.

In the simplified model illustrated in Figure 5 only the aforementioned 4 kernels,  
the linear kernel, two second orders kernels, and a third order kernel are present. In  
practice, if a nonlinearity were very strong, the Volterra Kernel model could have 16  
kernels or more if N greater than 5 (where N is the number of most recently transmitted  
15 bits to be considered). In the present embodiment out of the 16 Volterra Kernels only  
the four illustrated in Fig. 5 are significant, the others are negligible.

In the present embodiment FIR 511 and FIR 513 are much more significant than  
FIR 515 and FIR 517, and in fact FIR 515 and FIR 517 could be completely neglected.

The Volterra Kernel model tends to simplify the description of the channel  
20 because it reduces the number of independent terms that need to be taken into  
account. Volterra Kernels may group together all the terms that are time-shifted  
versions of each other. In the more general Volterra Series description, all the terms  
are represented independently. When groups of terms of a Volterra Series are time-  
shifted versions of each other, they may be associated with each other, and all the ones  
25 that are time-shifted versions of each other may be grouped as a single Volterra Kernel.

The two equivalent representations - the look-up table model and the Volterra  
Kernel model are mathematically equivalent because the Hadamard transformation can  
transform one into the other. The reason to choose one or the other is essentially ease  
of implementation. The model that is simpler is commonly dependent on the particular  
30 problem that is trying to be solved. For example, if a strongly nonlinear function with  
short memory is present (meaning small amounts of dispersion) the look-up table  
probably provides a simpler model. The look up table is likely simpler because, if the  
dispersion is not large N will not be large. If N is not large then  $2^N$  is not a very large  
number of coefficients. But if the memory span of the nonlinearity (i.e. N) grows then  
35 the look-up table grows exponentially because the size of the look-up table is  $2^N$ . The  
size of the look up table may become prohibitively complex for large N. In some cases



1 Volterra Kernels may provide a simpler model when  $N$  is large and the nonlinearity has a simple form which can be described with few kernels, such as the previous example that could be limited to two kernels.

5 If  $N$  is large, it will generally indicate that there is a lot of dispersion in the channel, but the form of the nonlinear function could be very simple. The function may be simple enough that it can be described, as in the previous example, by only two Volterra Kernels. If  $N$  is large and the Volterra model is simpler, the nonlinearity may be completely modeled with two kernels, even though  $N$  is very large. Accordingly in some cases the Volterra Kernel description is simpler. In other cases the look-up table  
10 description is simpler.

In the studies performed, the amount of dispersion necessitated an  $N$  on the order of 5, but in principle, for severely bandwidth limited fibers,  $N$  could be larger. In the case where two Volterra Kernels are sufficient to create an accurate channel model, regardless of how large  $N$  is, the Volterra Kernel description is generally simpler.

15 Figure 6 is a graph illustrating channel measurement, of a channel having an 850 nanometer VCSEL laser and fiber F0, and comparing the signal measurement with linear and nonlinear fiber models. In Figure 6 the solid line corresponds to the observations, the dotted line represents the linear model, and the dashed and dotted represents the nonlinear model. As can be seen from 601, 603 and 605 the nonlinear  
20 model approximates the measurements of the channel to a greater degree than the linear model. Accordingly if the channel model were limited to a linear model a good fit for the transmitted data would not be achieved. In contrast using the nonlinear model a significantly closer fit may be obtained.

25 Figure 7 is a graph illustrating channel measurement of a channel having an 850 nanometer VCSEL laser and fiber F0, and comparing the signal measurement with amount of error generated by linear and nonlinear channel models. Figure 7 is a graph representing the same time as the graph of Figure 6 except that the errors instead of the signals themselves are shown. In Figure 7 the linear model error is represented by the lines with circles and the nonlinear model is represented by the dotted line. As can  
30 be readily appreciated, by observing the nonlinear model points at 701 A, B, and C and comparing it with the linear model points at 703 A, B, and C the nonlinear model achieves a significantly smaller error.

35 Figure 8 is a graph representing the impulse response and a second order Volterra Kernel for a channel having an 850 nanometer wavelength VCSEL laser and utilizing fiber F0. Figure 8 illustrates an impulse response (the linear term of the overall response) at 801. Figure 8 also illustrates the response of the second order Volterra

1 Kernel at 803. In the present embodiment, the second order Volterra Kernel, which is  
associated with products of two consecutive bits, is the only significant nonlinear kernel.  
So the response of the second order Volterra Kernel generated from the product  $A_N \times$   
5  $A_{N-1}$ , i.e. FIR 513 in figure 5. FIR 511 corresponds to the linear kernel response 801  
and FIR 513 corresponds to the second order response 803. Using just the Volterra  
Kernels of FIR 511 and FIR 513 a close approximation of the channel which includes  
nonlinear elements and memory was achieved. The same method was used to  
examine the remaining fibers in the table of Figure 3. The signal-to-noise ratio for the  
10 linear model and for the nonlinear model (which was a linear model with nonlinear  
addition) was computed for each fiber.

Signal-to-noise ratio is defined as 10 times the base 10 log of the signal power  
divided by the error power. To compute the signal-to-noise ratio the power for the  
signal was computed. The sum of the squares of the samples of the signal yields the  
total power of the signal and the sum of the squares of the samples of the error yields  
15 the error power.

There are two versions of the error power, one of them for the linear model  
containing one Volterra Kernel and the other for the nonlinear model containing the  
additional nonlinear Volterra Kernels. The result of the error computations for the linear  
and the nonlinear model is illustrated in the table of figure 9. As can be seen from the  
20 table of figure 9 the signal-to-noise ratio for the linear model is in the range of 12 to 13  
dB. In the nonlinear model the error is significantly smaller, and correspondingly the  
signal to noise ratio is significantly higher in the range of 23 to 25 dB. The nonlinear  
model yields a model having approximately a 10 to 13 dB better signal to noise ratio,  
which is a significant improvement.

25 The previously described measurements were all done at 850 nanometers  
wavelength. In the measurements taken, the nonlinearity was much larger at 850  
nanometers than at 1310 nanometers. If the same measurements are repeated at  
1310 nanometers, the linear model appears to be very adequate.

Figure 10 is a graph of measured signal vs. linear model and the error between  
30 the measured signal and the linear model. Accordingly with the present data rate and  
fibers the linear channel model at 1310 nanometers appears to be fairly accurate. The  
graph of figure 10 illustrates the measured signal as a solid line. The graph of figure  
10 is the result of a linear model shown as the line with circles. The line with diamonds  
represents the error.

35 Figure 11 is a graph of the impulse response and a second order Volterra Kernel  
for the channel comprising fiber F0 and a DFB laser having a 1310 nano-meter

1 wavelength. The impulse response is illustrated at 1101 and the second order Volterra Kernel is illustrated at 1103. The second order Volterra Kernel is almost zero and most likely would not have to be taken into account in a model of the channel.

5 Figure 12 is a table of signal-to-noise ratios for a linear channel model having a DFB laser operating at a wavelength of 1310 nanometers. All of the channel signal to noise ratios of all measured channels operating at a wavelength of 1310 nanometers were in the range of 26 to 28 dB indicating that a nonlinear term may not be necessary at a wavelength of 1310 nanometers, for a one gigahertz data rate.

10 Additionally measurements were done including cases where mechanical motion of a fiber was introduced during the measurement process to examine motion induced nonstationarity of the general response. These observations for nonstationarity were done because there is some belief that the optical channel is not fixed in time and if vibration is introduced in the fiber some redistribution of the modes in the fiber may change the response of the fiber and accordingly the channel may be time-dependent.  
15 No evidence of any significant change in the fiber response as a result of motion was observed.

Slow changes in the channel may be compensated by the LMS algorithm adjusting the channel model to track those types of changes.

20 A program listing of a computer program used for the channel studies is included as Appendix A. Essentially, the program takes an input block of data from the measurements processes it, and then trains the canceller. It then computes the Volterra Kernels coefficients of the model using the linear model or the nonlinear model. The program computes a signal to noise ratio and it prints out the results.

25 Figure 13 is a block diagram of an optical receiver including a nonlinear optical channel equalizer. The nonlinear optical channel equalizer 1300 accepts a signal which includes linear and nonlinear components.

30 The electrical signal commonly results from converting an optical signal to the electrical domain using an optical to electrical converter 1307, such as for example a PIN diode, avalanche photodetector (APD), or another detector. The optical to electrical converter signal is amplified using a transimpedance amplifier (TIA) 1309 and a postamplifier 1311. The postamplifier 1311 generally should not hard-limit a signal provided to it as hard limiting may introduce nonlinearity.

35 After processing the signal provided to it the postamplifier 1311 may provide a processed signal to an optional analog processing block 1313. The analog processing block 1313 may provide such analog processing as filtering and automatic gain control, prior to providing an output signal to an analog to digital converter 1315. The output

1 signal from the analog to digital converter converts the electrical signal provided by the  
optional analog processing block 1313 to a multibit digital representation, prior to  
providing the multibit digital representation to a nonlinear optical channel equalizer  
1300. The nonlinear optical equalizer 1300 operates in the digital domain, and may be  
5 implemented using special-purpose digital logic or a general purpose programmable  
digital signal processor. Prior to entering the nonlinear optical equalizer 1300 the  
multibit signal may undergo additional preprocessing steps such as filtering, linear  
equalization, interference cancellation, etc. in an optional digital processing block 1317.  
Equalizer 1300 is a decision feedback equalizer comprising a detector such as slicer  
10 1303, a compensator such as subtractor 1301 and a feedback block 1305. The  
feedback block 1305 includes a nonlinear channel estimator employing a lookup table  
as illustrated in Figure 4 or the Volterra Kernel approach as illustrated in Figure 5. A  
difficulty with using the look up table approach of Figure 4 or the Volterra Kernel as  
illustrated in Figure 5 is that in both cases the Volterra Kernel or look up table  
15 coefficients need to be identified. One solution to the problem of coefficient  
identification is to have the transmitter send a training sequence, which is known a  
priori, to the receiver. The nonlinear channel estimator 1305 can then be trained using  
the known training sequence. In such a case, the functioning of the nonlinear channel  
estimator 1305 would proceed as in Figure 4 or Figure 5 as the bit sequence would be  
20 known and differences produced by the channel could be readily identified.

In practice, a training sequence may not be required because the decisions 1307  
of the decision feedback equalizer 1300 and the nonlinear channel estimator 1305 may  
still converge. Initially, because the channel estimator 1305 is not trained, the decisions  
1307 will have multiple errors. There is however, in most channels, a bias towards  
25 good decisions. Most decision feedback equalizers will converge if the channels do not  
exhibit excessive intersymbol interference (ISI). Accordingly, if the coefficients in the  
nonlinear channel estimator 1305 are incorrect initially, there are both good and bad  
decisions. As long as the good decisions outnumber the bad decisions, there will be  
a converging trend and the nonlinear channel estimator 1305 will eventually tend to  
30 converge.

The nonlinear channel estimator 1305 may also be trained using an LMS  
algorithm as illustrated in Figure 4 or 5. As the coefficients begin improving in the  
nonlinear channel estimator 1305, the improvement helps make a larger percentage of  
correct decisions, which further assists in the convergence of the nonlinear channel  
35 estimating filter 1305. Once the values in the estimating filter converge, the nonlinear  
channel estimator 1305 will have modified the coefficients so that essentially all correct

1 decisions are made. Any incorrect decisions made by the system tend to corrupt the  
values in the nonlinear channel estimator 1305, however, as long as the correct  
decisions outnumber the incorrect decisions the nonlinear channel estimator will  
converge to an essentially correct solution. In other words, as long as the majority of  
5 decisions are correct the coefficients of the nonlinear channel estimator 1305 will have  
a net movement in the correct direction and converge.

Once there is an initial convergence in the nonlinear channel estimator 1305 the  
signal to the slicer 1303 is improved because at least some of the intersymbol  
interference is cancelled in summation unit 1301. As a result the number of correct  
10 decisions 1307 increases which leads to a better channel estimation. Past decisions  
are stored within the nonlinear channel estimator 1305 and are used to compute a  
replica of the intersymbol interference in order to provide it to summation unit 1301.

If a Volterra Kernel structure similar to Figure 5 is used for the nonlinear channel  
estimator then the memory of past decisions are stored in the FIR filters 511 through  
15 517, which each nominal contain a FIR delay line structure. If the look up table  
approach is used then the memory for the past decisions are stored within a shift  
register, such as that illustrated in 407 at Figure 4.

Figure 14A is a block diagram of an exemplary nonlinear channel equalizer as  
may be used in the nonlinear decision feedback equalizer of Figure 13. The nonlinear  
channel estimator Figure 14 is similar to the Volterra Kernel model illustrated in Figure  
20 5. The Volterra Kernel model of Figure 5 was used as an illustration of characterization  
of the channel. The nonlinear channel estimator illustrated in Figure 14 has an LMS  
update loop similar to Figure 5. Additionally, similar to Figure 5, the number of Volterra  
Kernels employed would depend upon the characteristics of the channel and the laser  
25 used to drive the channel.

In Figure 14A, a signal 1427, which has been provided from an optical channel  
and converted to an electrical signal, is accepted by an optical channel equalizer,  
shown generally at 1400. The equalizer 1400 accepts the signal 1427 into a summation  
unit 1301 where a (negated) correction signal 1429, representing the predicted inter-  
30 symbol interference, is added. Prior to the training and convergence of the Volterra  
Kernel estimator correction signal is zero or an arbitrary value. Slicer 1303 makes  
decisions 1307 as to the values of the signal transmitted. Decisions 1307 are accepted  
by Volterra Kernel estimator 1401, which models the nonlinearities of the channel that  
provides the signal to the equalizer 1400. The output of the Volterra Kernel estimator  
35 provides a value of predicted intersymbol interference 1429, which can then be  
subtracted from the accepted signal in order to accurately recreate a transmitted signal

1 which has been transmitted.

The error in the predicted intersymbol interference 1429 is estimated by comparing decisions 1307 from slicer 1303 with the input signal 1422, which has been adjusted in summation unit 1301 by removing the predicted intersymbol interference ISI 1429. The decisions 1307 and error 1425 are used to adjust the FIR filters 511, 513, 515, and 517, which exemplarily illustrate the FIR filters which comprise the Volterra Kernel estimator 1401. In such a manner, the Volterra Kernel estimator may be trained and compensate for non-linearities within the channel that provides the signal to the equalizer 1400.

10 Figure 14B is an exemplary block diagram of a non-linear optical channel equalizer employing a lookup table channel estimator, according to the embodiment of the invention. In Figure 14 B an LMS algorithm may be employed in adjusting the values within the look up table 1435. The system 14B may be operated so that training of the equalizer is accomplished by processing of a signal provided from an optical channel, determining error signals and adjusting the equalizer 1401. In such a manner the equalizer may be trained to model the channel parameters. Those skilled in the art will recognize that the equalizers may be trained by employing a known sequence. Because such a sequence is known a priori the difference between the response of the channel and the desired response of the channel, i.e., the known sequence, can be readily determined. Such sequences may shorten the time necessary to train a nonlinear optical channel equalizer.

20 A nonlinear channel estimator could also be built based on the look up table approach illustrated in Figure 4. The implementation of such a look up table version is a straight-forward adaptation of the channel characterization circuit illustrated in Figure 4.

25 Figure 15 is a block diagram of a nonlinear channel estimator combined with a Viterbi decoder. Instead of a decision feedback equalizer a Viterbi decoder may be used. Nonlinear channel estimator 1501 would be used to compute the expected signal going to the branch metric computations 1503. The remainder of the Viterbi decoder system including the actual Viterbi decoder itself, block 1505, is similar to the linear case. The nonlinear channel estimator 1501 is creating a model of the received signal. If the nonlinear channel estimator 1501 has a memory comprising  $k$  bits, that is it remembers the last  $k$  inputs, then the Viterbi decoder 1505 would have  $2^{(k-1)}$  states. Therefore, if  $k=3$  then the Viterbi decoder 1505 would be a 4 state Viterbi decoder. If the nonlinear channel estimator 1501 has a memory of 3 bits then it can support eight different expected values of the received signal. Which would be implemented with a

1 look up table have eight locations. The expected values of the received signal are used  
by the branch metric computations 1503 to compute all the branch metrics in the Viterbi  
decoder.

5 The Viterbi decoder illustrated in Figure 15 is the same as a standard type Viterbi  
decoder except for the fact that the channel estimator function is a nonlinear channel  
estimator with memory. The nonlinearity is expressed either in the form of a look up  
table or a Volterra Kernel.

10 The Viterbi decoder includes a receiver for receiving a signal including linear and  
non linear components. A non linear channel estimator computes the expected values  
of the received signal. A branch metrics computer computes the branch metrics based  
on the expected values of the received signal. A standard Viterbi decoder accepts the  
computed branch metrics and decodes the received signal. The non linear channel  
estimator can be fabricated using a Volterra kernel estimator or a lookup table estimator  
as illustrated at 1401 as illustrated at 1433 in Figure 14A or a look up table  
15 implementation as illustrated at 1433 in Figure 14B.

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1 WHAT IS CLAIMED IS:

1. A method for modeling the behavior of a data channel the method comprising:

5 determining a sequence of data input to the data channel;  
using at least part of the sequence of data input to the data channel as an index to a channel model value;

sampling the data after it has passed through the channel to produce a sampled value;

10 comparing the channel model value with the sampled value; and  
adjusting the channel model value based on the results of the comparison between the channel model value and the sampled value.

2. A method as in claim 1 wherein determining a sequence of data input to the data channel comprises determining the last N bits input to the channel.

15 3. A method as in claim 2, where  $N = 5$ .

4. A method as in claim 1 wherein the sampling of the data after it has passed through the channel to produce a sampled value comprises producing a real number representing the sampled value.

20 5. A method as in claim 1, wherein adjusting the channel model value further comprises adjusting the channel model value according to an LMS (Least Means Squared) algorithm.

25 6. A method as in claim 1 wherein adjusting the channel model value further comprises adjusting the channel model value until it converges.

7. A method as in claim 6 further comprising converting the look up table into Volterra Kernels.

30 8. A method as in claim 7 further comprising converting the look up table into Volterra Kernels using a Hadamard transform.

35 9. A method as in claim 7 further comprising adjusting the Volterra Kernels based on the results of the comparison between the channel model value and the sampled value.



1           10. A method as in claim 9 further comprising eliminating the insignificant Volterra Kernels.

5           11. A method for modeling the behavior of a data channel the method comprising:

          determining a sequence of data input to the data channel;  
          determining a Volterra Series representation of the channel;  
          accepting at least part of the sequence of data input to the data into the Volterra series representation of the channel to produce a channel model value;  
10          sampling the data after it has passed through the channel to produce a sampled value;  
          comparing the channel model value with the sampled value; and  
          adjusting the channel model value based on the results of the comparison between the channel model value with the sampled value.

15          12. A method as in claim 11 wherein determining a Volterra Series representation of the channel comprises:

          accepting a most recent value of the sequence of data input to the data channel;  
          accepting the most recent value of the sequence of data input to the data channel into a first FIR (Finite Impulse Response) filter;

20          accepting a product of the most recent value of the sequence of data input to the data channel and a second most recent value of the sequence of data input to the data channel into a second FIR; and

          summing an output of the first FIR and output of the second FIR to form the channel model value.

25          13. A method as in claim 11 wherein determining a Volterra Series representation of the channel comprises:

          accepting a most recent value of the sequence of data input to the data channel;  
          accepting the most recent value of the sequence of data input to the data channel into a first FIR filter;

30          accepting a product of the most recent value of the sequence of data input to the data channel and the second most recent value of the sequence of data input to the data channel into a second FIR;

          accepting a product of the most recent value of the sequence of data input to the data channel and a third most recent value of the sequence of data input to the data channel into a third FIR; and

35          summing an output of the first FIR and output of the second FIR and output of the

1 third FIR to form the channel model value.

14. A method as in claim 11 wherein determining a Volterra Series representation of the channel comprises:

5 accepting a most recent value of the sequence of data input to the data channel;  
accepting the most recent value of the sequence of data input to the data channel into a first FIR filter;

accepting a product of the most recent value of the sequence of data input to the data channel and the second most recent value of the sequence of data input to the data channel into a second FIR;

10 accepting a product of the most recent value of the sequence of data input to the data channel and a third most recent value of the sequence of data input to the data channel into a third FIR;

accepting a product, said product being the most recent value of the sequence of data input to the data channel and the two next most recent data input, into a fourth FIR; and

15 summing an output of the first FIR and output of the second FIR and output of the third FIR and output of the fourth FIR to form the channel model value.

20 15. A method as in claim 11 wherein the difference between the channel model value and the output of the channel is used to update all the FIRs.

16. A method as in claim 12 wherein the difference between the channel model value and the output of the channel is used to update all the FIRs.

25 17. A method as in claim 13 wherein the difference between the channel model value and the output of the channel is used to update all the FIRs.

18. A method as in claim 14 wherein the difference between the channel model value and the output of the channel is used to update all the FIRs.

30 19. A method as in 15 wherein an LMS algorithm is used to update all the FIRs.

20. A method as in 16 wherein an LMS algorithm is used to update all the FIRs.

35 21. A method as in 17 wherein an LMS algorithm is used to update all the FIRs.

1           22. A method as in 18 wherein an LMS algorithm is used to update all the FIRs.

          23. A method for equalizing an optical signal, modulated with a digital signal;  
received over an optical channel, the method comprising:

5           converting the optical signal into an electrical signal;

          summing the electrical signal with a correction signal;

          providing the summed signal to a detector;

          detecting the summed signal to produce decisions;

          providing the decisions to a nonlinear channel estimator; and

10          estimating the correction signal in the nonlinear channel estimator.

          24. The method of claim 23 wherein estimating the correction signal in the  
nonlinear estimator further comprises:

          accepting the decisions;

15          predicting the inter-symbol interference of the channel in a nonlinear channel  
estimator; and

          forming a correction signal from the predicted inter-symbol interference.

          25. The method of claim 24 wherein predicting the inter-symbol interference  
of the channel further comprises:

20          providing the decisions to a plurality of Volterra Kernels; and

          summing the output of the plurality Volterra Kernels to form a correction signal.

          26. The method of claim 25 further comprising:

          comparing the predicted inter-symbol interference to inter-symbol interference in  
the electrical signal; and

25          updating the Volterra Kernels based on the result.

          27. The method as in claim 26 wherein updating the Volterra Kernels  
comprises using a LMS (Least Means Squared) algorithm to update the Volterra  
Kernels.

30          28. The method of claim 24 wherein predicting the inter-symbol interference  
of the optical channel further comprises:

          providing the data decisions as an address into a look up table;

          outputting a value stored in the look up table as the predicted inter-symbol  
interference;

35          comparing the predicted inter-symbol interference to the inter-symbol interference

1 in the electrical signal; and  
updating the value stored in the look up table based on the result.

29. The method as in claim 28 wherein updating the value stored in the look  
5 up table comprises using a LMS (Least Means Squared) algorithm.

30. An apparatus for equalizing a signal received over an optical channel, the  
apparatus comprising:

an input that accepts an optical signal;  
a converter that converts the optical signal into an electrical signal;  
10 a summation unit that sums the electrical signal with a correction signal;  
a detector that detects the summed signal to produce decisions; and  
a nonlinear channel estimator that estimates the correction signal.

31. The apparatus of claim 30 wherein the nonlinear estimator further  
15 comprises:

an input that accepts the decisions;  
an estimating circuit that predicts the inter-symbol interference of the channel;  
and  
an output that provides a correction signal from the estimated inter-symbol  
20 interference.

32. The apparatus of claim 31 wherein estimating circuit that estimates the  
intersymbol interference of the channel further comprises:

a plurality of Volterra kernels that accept the decisions and produce individual  
outputs; and  
25 a summation unit that sums the individual outputs of the plurality of Volterra  
Kernels to form a correction signal.

33. The apparatus of claim 32 further comprising:

a comparator for comparing the predicted inter-symbol interference to the inter-  
30 symbol interference in the electrical signal; and  
means for updating the Volterra kernels based on the result.

34. The apparatus as in claim 33 wherein the comparator that compares the  
predicted inter-symbol interference to the inter-symbol interference in the electrical  
35 signal includes a LMS (Least Means Squared) algorithm that compares the predicted  
inter-symbol interference to the inter-symbol interference in the electrical signal.

1           35. The apparatus of claim 31 wherein the estimating circuit that estimates the intersymbol interference further comprises:

          a look up table which accepts the data decisions as an address into the look up table;

5           values of the predicted inter-symbol interference stored in the look up table;

          a subtractor that subtracts the predicted inter-symbol interference from the electrical signal to produce a signal substantially free from intersymbol interference;

          a second subtractor that subtracts the decision from the substantially inter-symbol interference free signal to produce an error;

          and

10          means for updating the value stored in the look up table based on the error.

          36. The apparatus as in claim 35 wherein comparing the comparator that compares the estimated inter-symbol interference to the inter-symbol interference in the electrical signal comprises a LMS (Least Means Squared) algorithm that compares the  
15          predicted inter-symbol interference to the inter-symbol interference in the electrical signal.

          37. A method for decoding a signal received over an optical channel, the method comprising:

20          receiving a signal including linear and non linear components;

          estimating, in a non linear channel estimator, the expected values of the received signal;

          computing the branch metrics based on the expected values of the received signal;

          providing the computed branch metrics to a Viterbi decoder; and

25          Viterbi decoding the received signal using the branch metrics provided to the Viterbi decoder.

          38. The method of claim 37 wherein estimating, in a non linear channel estimator, the expected values of the received signal comprises:

30          providing the value of the received signal to a Volterra kernel estimator; and

          computing the expected value sent based on the output of the Volterra kernel estimator.

          39. The method of claim 37 wherein estimating, in a non linear channel estimator, the expected values of the received signal comprises:

35          providing the value of the received signal as an address to a look up table; and

1 looking up the stored value as the actual value transmitted .

40. An apparatus for decoding a signal received over an optical channel, the apparatus comprising:

5 a receiver for receiving a signal including linear and non linear components;  
a non linear channel estimator that computes the expected values of the received signal;

a branch metrics computer for computing the branch metrics based on the expected values of the received signal;

10 a Viterbi decoder that accepts the computed branch metrics and  
Viterbi decodes the received signal.

41. The apparatus of claim 40 wherein the non linear channel estimator that computes the expected values of the received signal comprises a Volterra kernel estimator that computes the expected value sent based on the output of the Volterra  
15 kernel estimator.

42. The apparatus of claim 40 wherein the non linear channel estimator that computes the expected values of the received signal comprises a look up table that uses the value of the received signal as an address to look up the stored value as the  
20 actual value transmitted .

43. A method for detecting digital data modulated on an optical signal and received over an optical channel, the method comprising:

converting the optical signal to an electrical signal;

25 converting the electrical signal to a multibit digital representation;

estimating distortion introduced in the optical signal by the optical channel;

compensating the multibit digital representation for the distortion; and

detecting the digital data from the compensated multibit digital representation.

44. A method as in claim 43 wherein estimating distortion introduced in the optical signal by the optical channel comprises estimating in a Volterra Kernel estimator the distortion introduced in the optical channel.  
30

45. A method as in claim 43 wherein estimating distortion introduced in the optical signal by the optical channel comprises estimating in a lookup table estimator the distortion introduced in the optical channel.  
35

1           46. An apparatus for detecting digital data modulated on an optical signal and  
received over an optical channel, the apparatus comprising:  
          a converter for converting the optical signal to an electrical signal;  
          an analog to digital converter that converts the electrical signal to a multibit digital  
5 representation;  
          an estimator that estimates distortion introduced in the optical signal by the  
optical channel;  
          a compensator that compensates the multibit digital representation for the  
distortion; and  
          a detector that detects the digital data from the compensated multibit digital  
10 representation.

          47. A method as in claim 45 wherein estimator that estimates distortion  
introduced in the optical signal comprises a Volterra Kernel estimator.

15           48. A method as in claim 45 wherein estimator that estimates distortion  
introduced in the optical signal comprises a lookup table estimator.

          49. An apparatus as in claim 46 wherein the estimator that estimates distortion  
introduced in the optical signal comprises a Volterra Kernel estimator.

20           50. An apparatus as in claim 46 wherein estimator that estimates distortion  
introduced in the optical signal comprises a lookup table estimator.

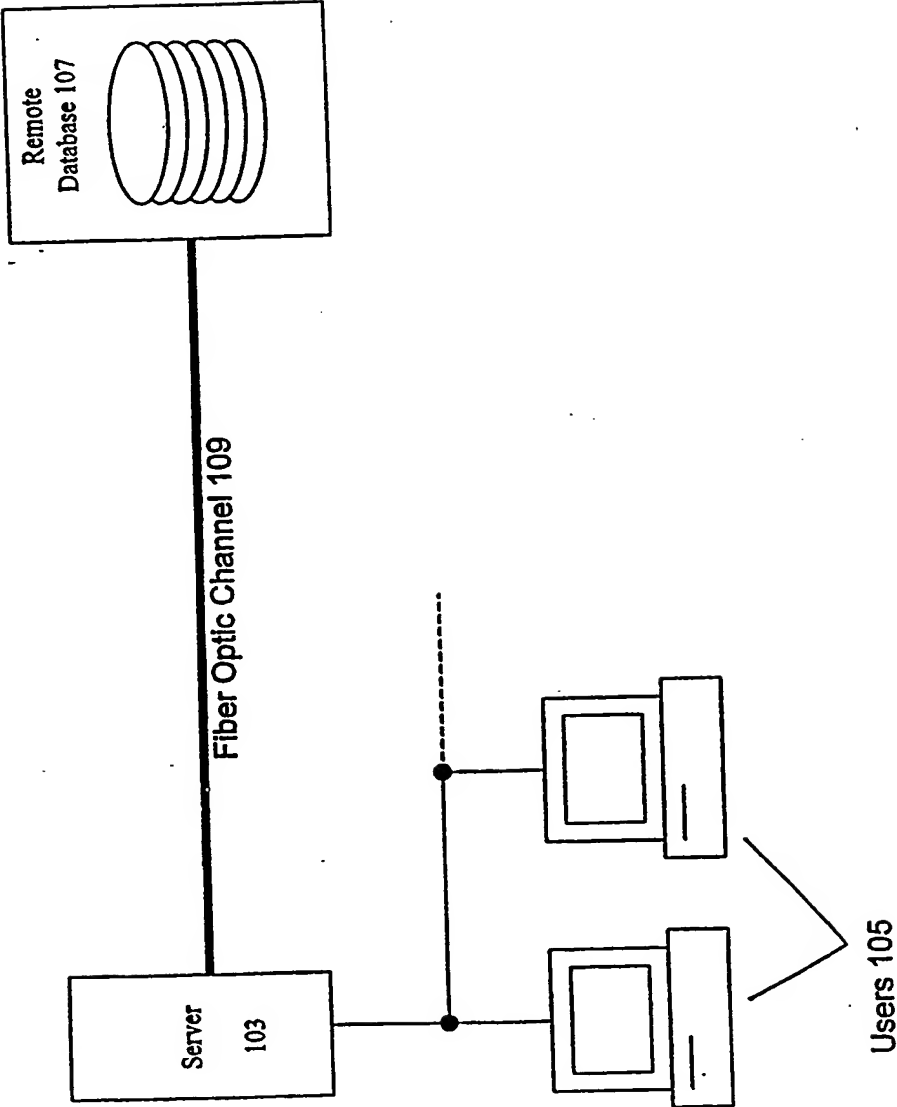


Figure 1



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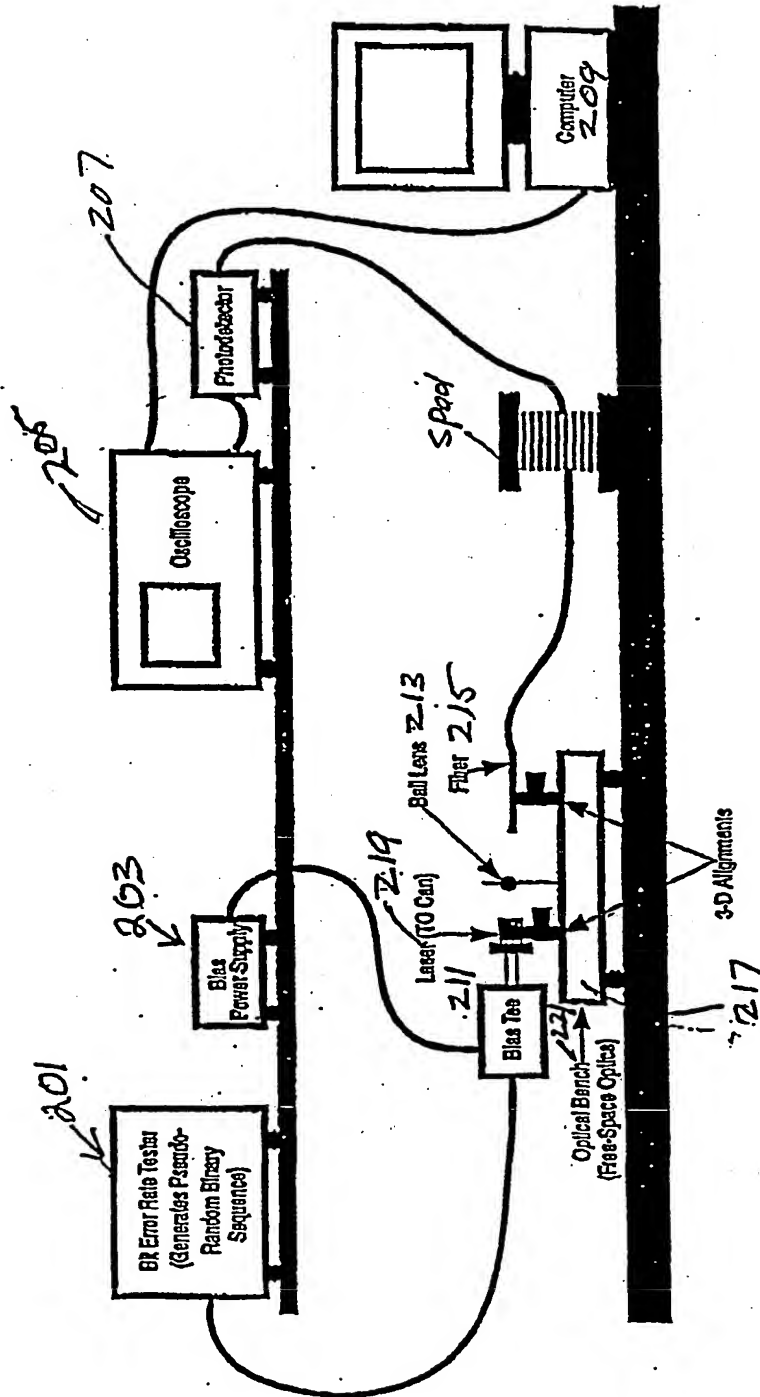


Figure #2

FIBER	CORE DIAMETER[ $\mu$ m]	LENGTH[m]	MANUFACTURER
F0	62.5	270	Fujikura
F1	50.0	1152	Corning
F2	62.5	2234	Corning
F3	50.0	2247	Corning
F4	62.5	1151	Corning
F5	50.0	540	Corning

Figure #3

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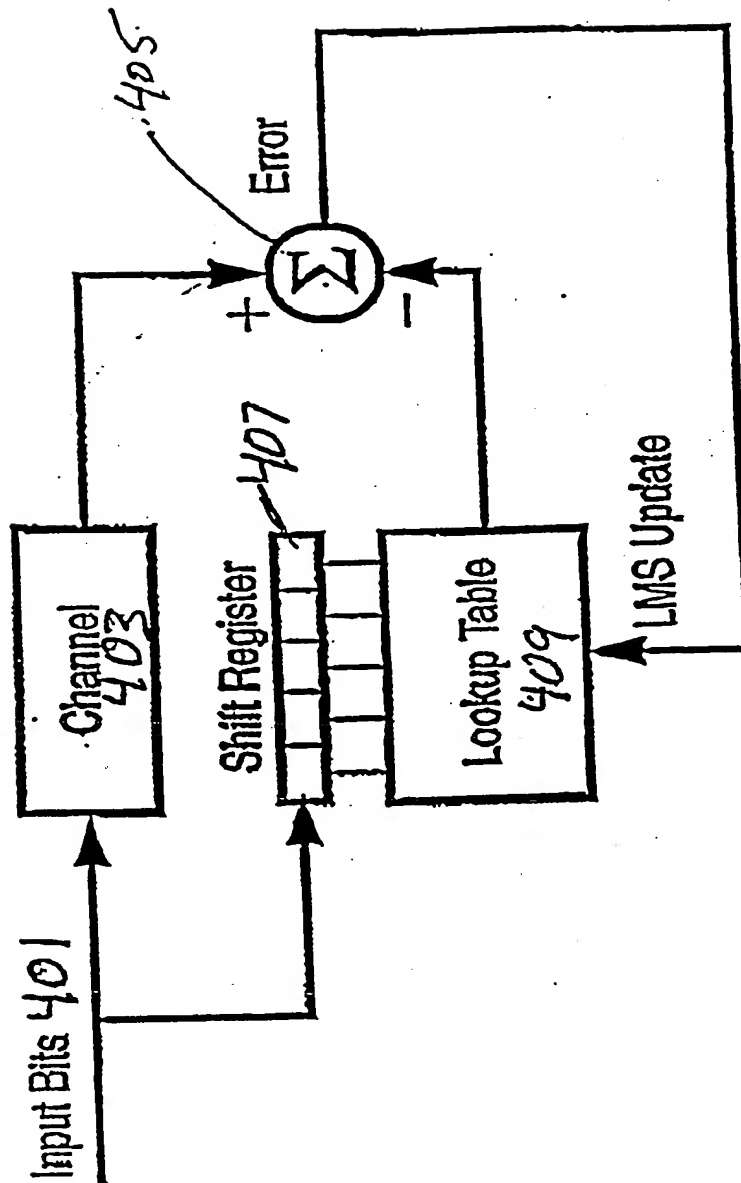
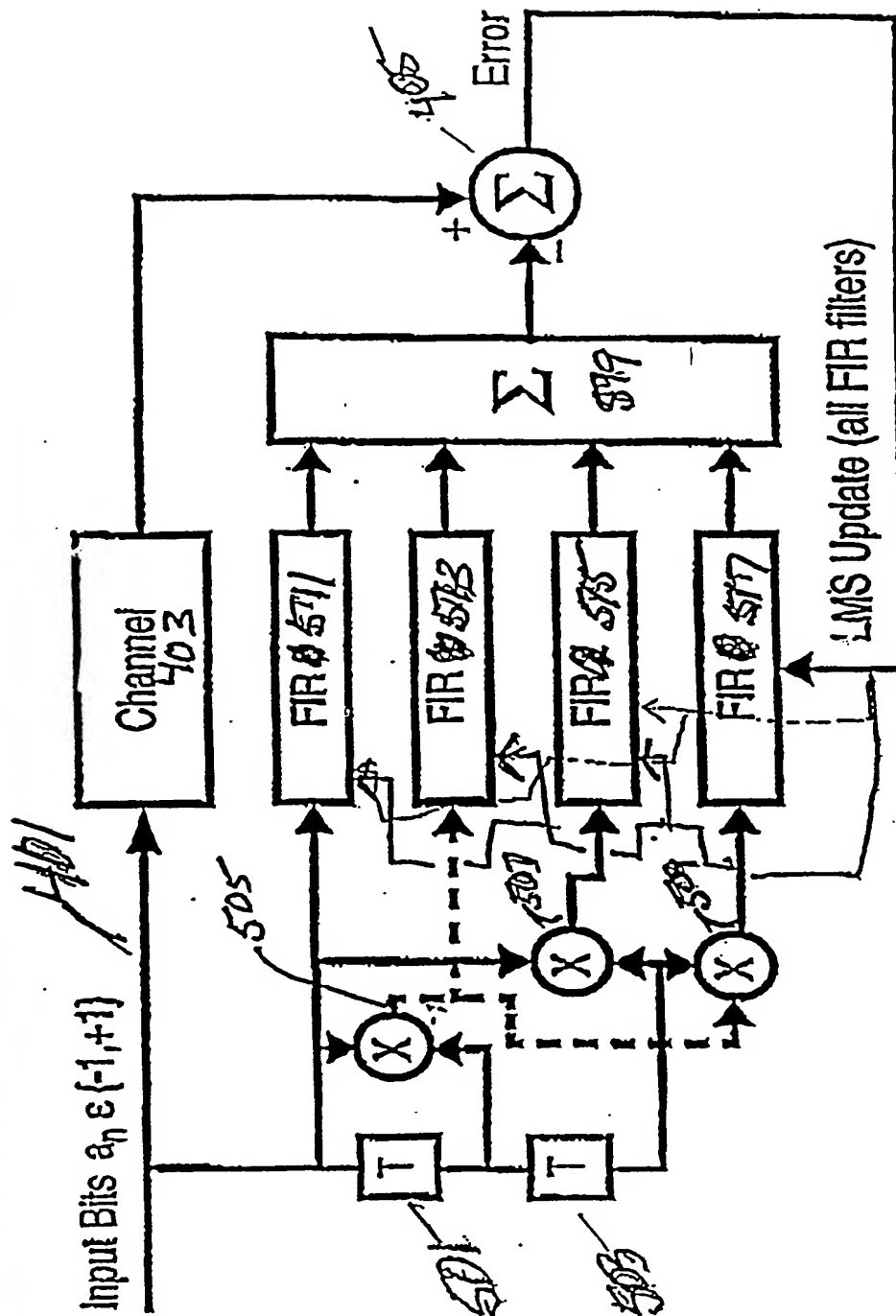


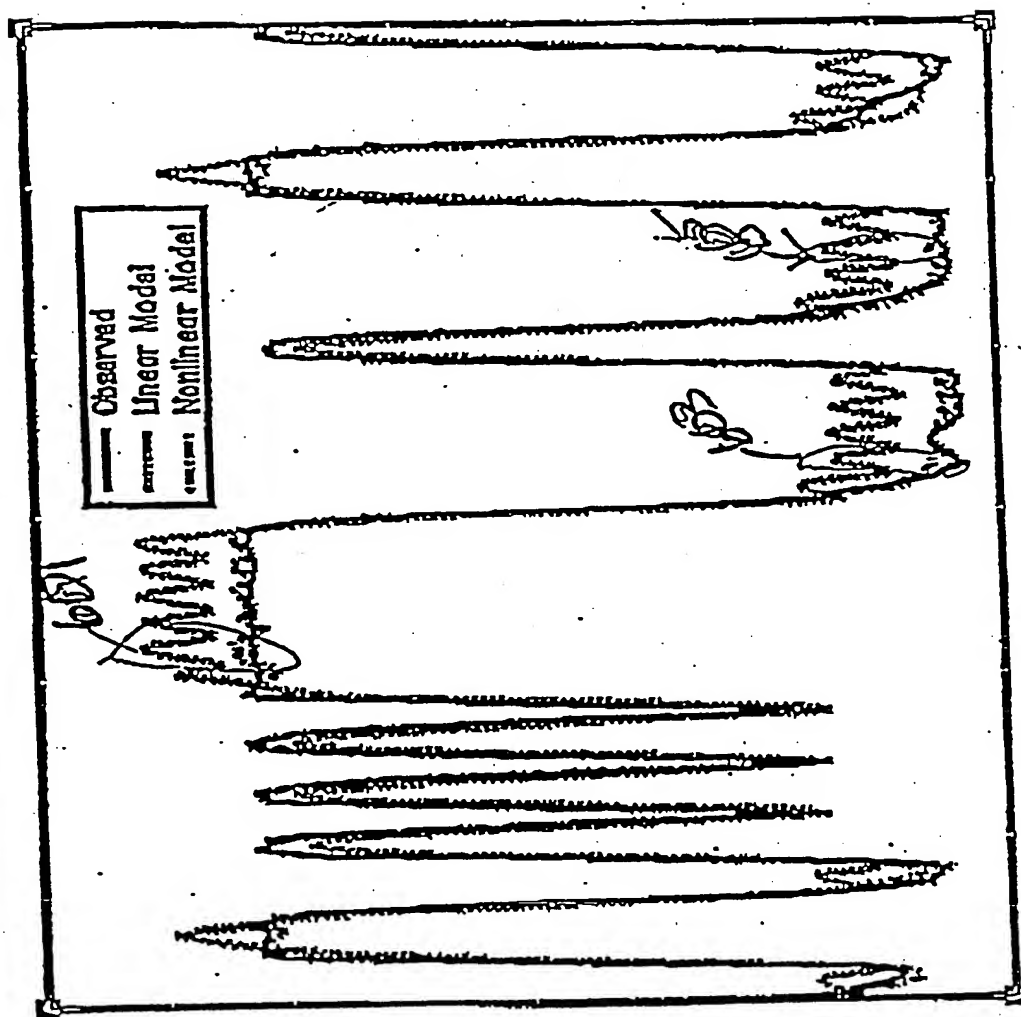
Figure 4



NOTE: This simplified diagram shows only four Volterra kernels, as with the data terms  $a_n$ ,  $a_n a_{n-1}$ ,  $a_n a_{n-2}$ , and  $a_n a_{n-1} a_{n-2}$

57

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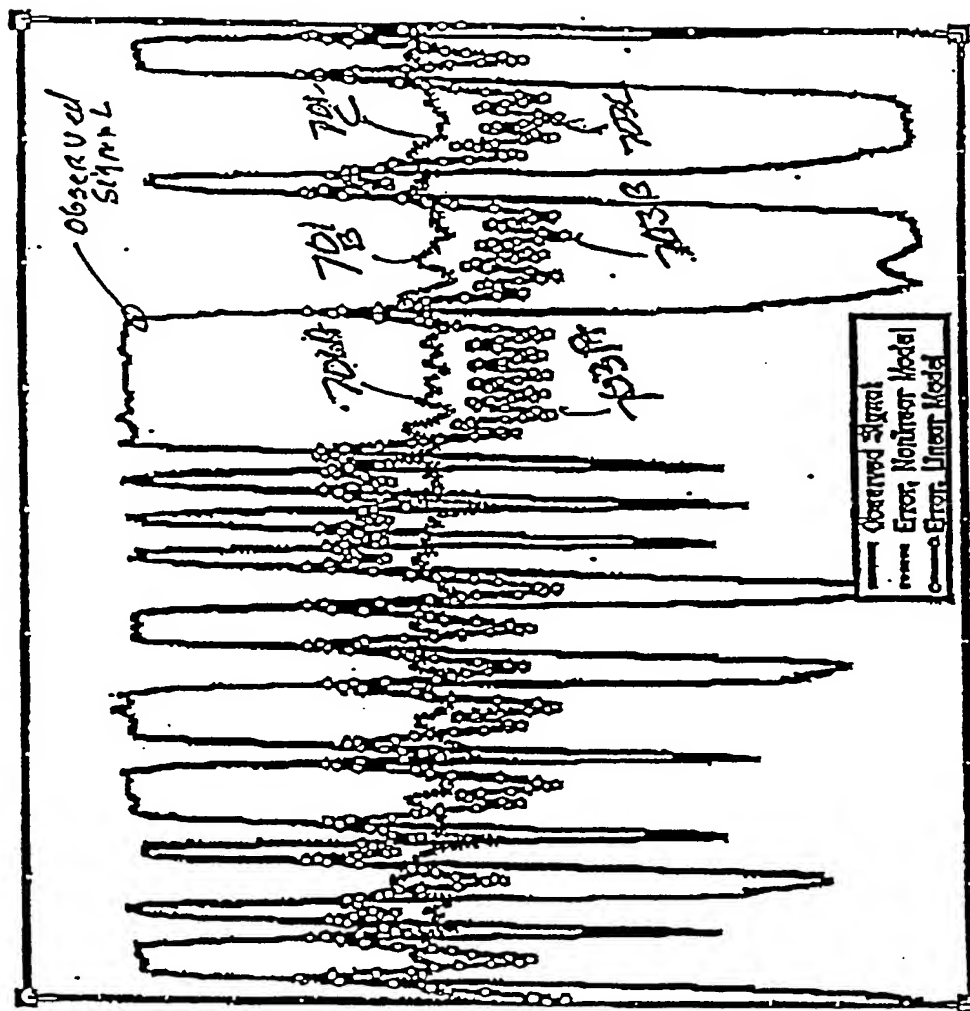


Figure 7

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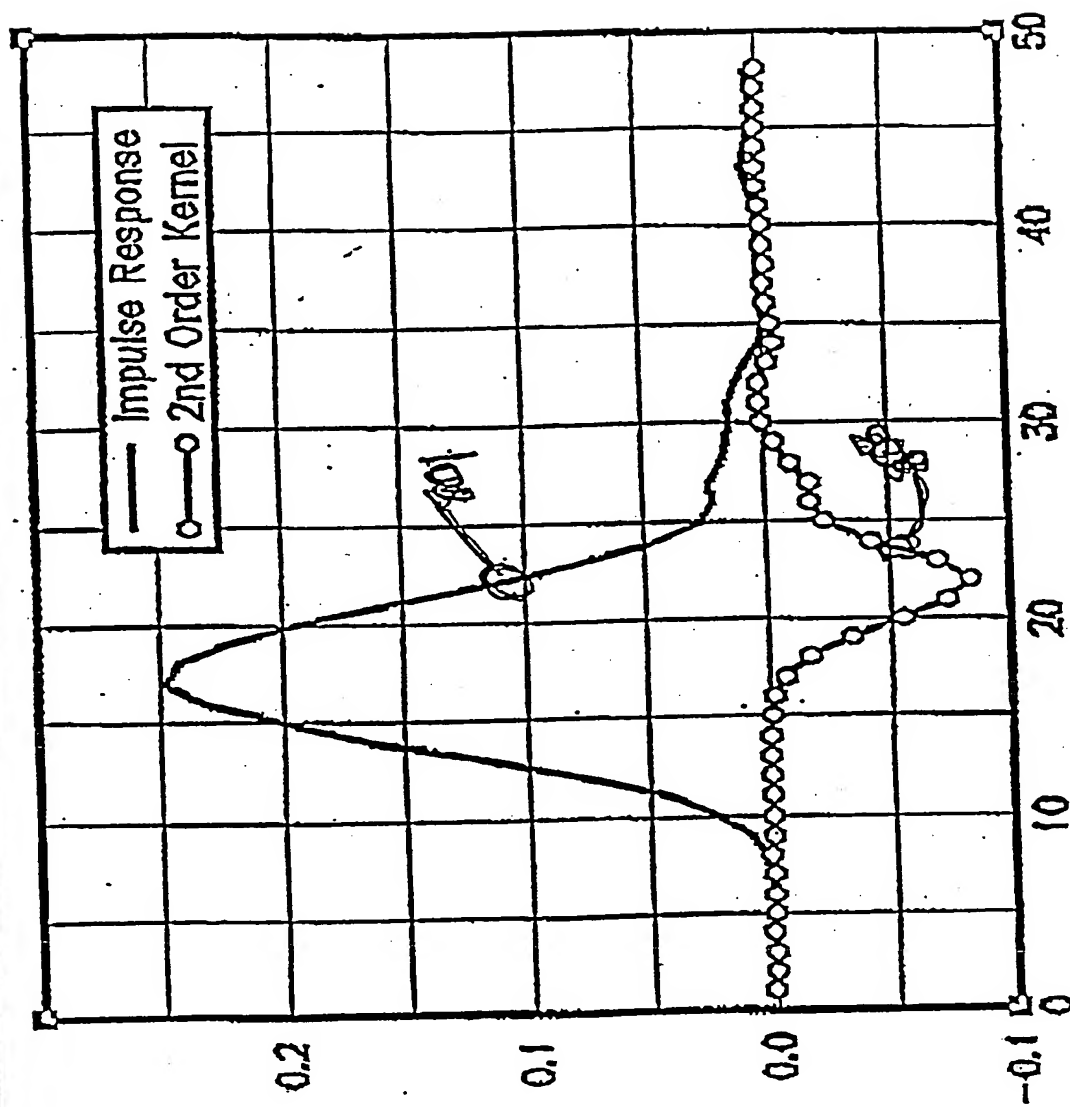


Figure 8

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FIBER	SNR [dB] (linear model)	SNR [dB] (nonlinear model)
F0	12.8	23.2
F1	12.1	24.7
F2	13.4	24.9
F3	13.3	23.7
F4	12.4	23.8
F5	12.5	23.7

NOTE: SNR is defined as  $10 \log_{10}(\text{Signal Power/Error Power})$ , and it does not necessarily coincide with the slicer SNR of a receiver

*Figure 9*



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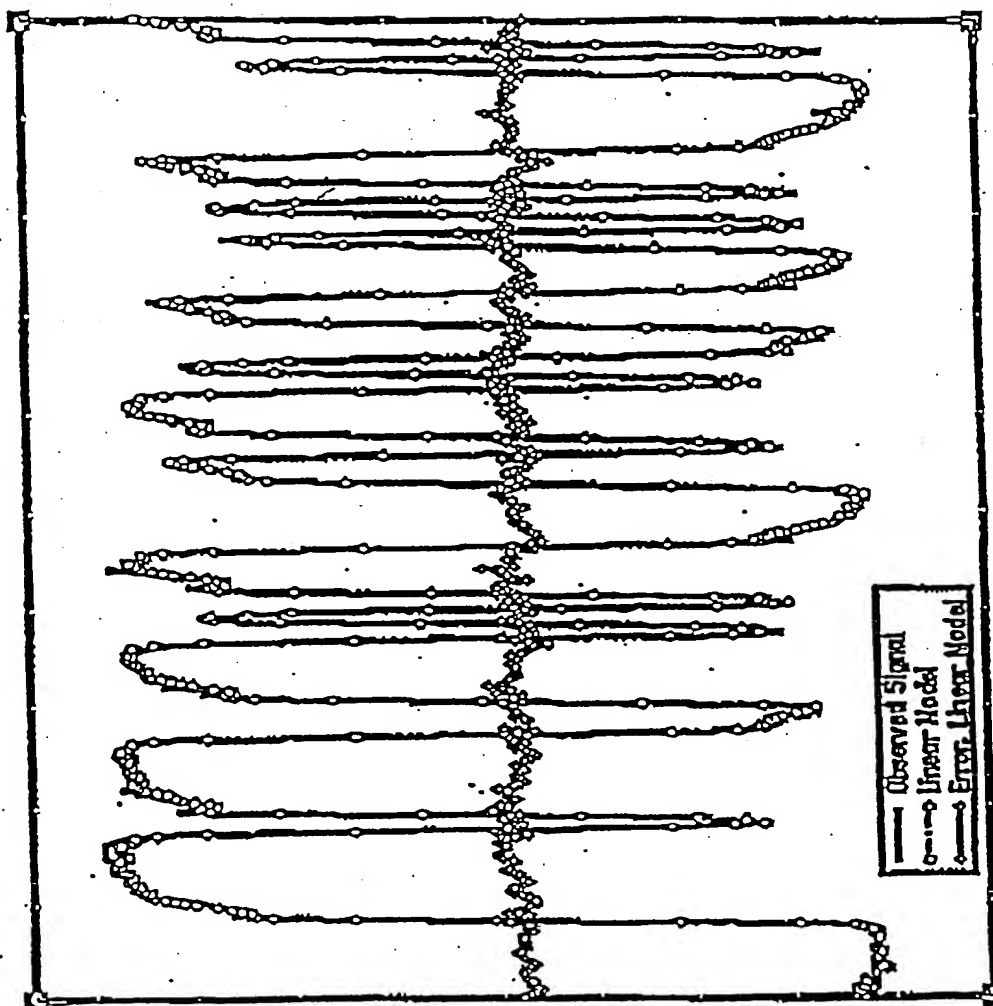


Figure 10

11/16

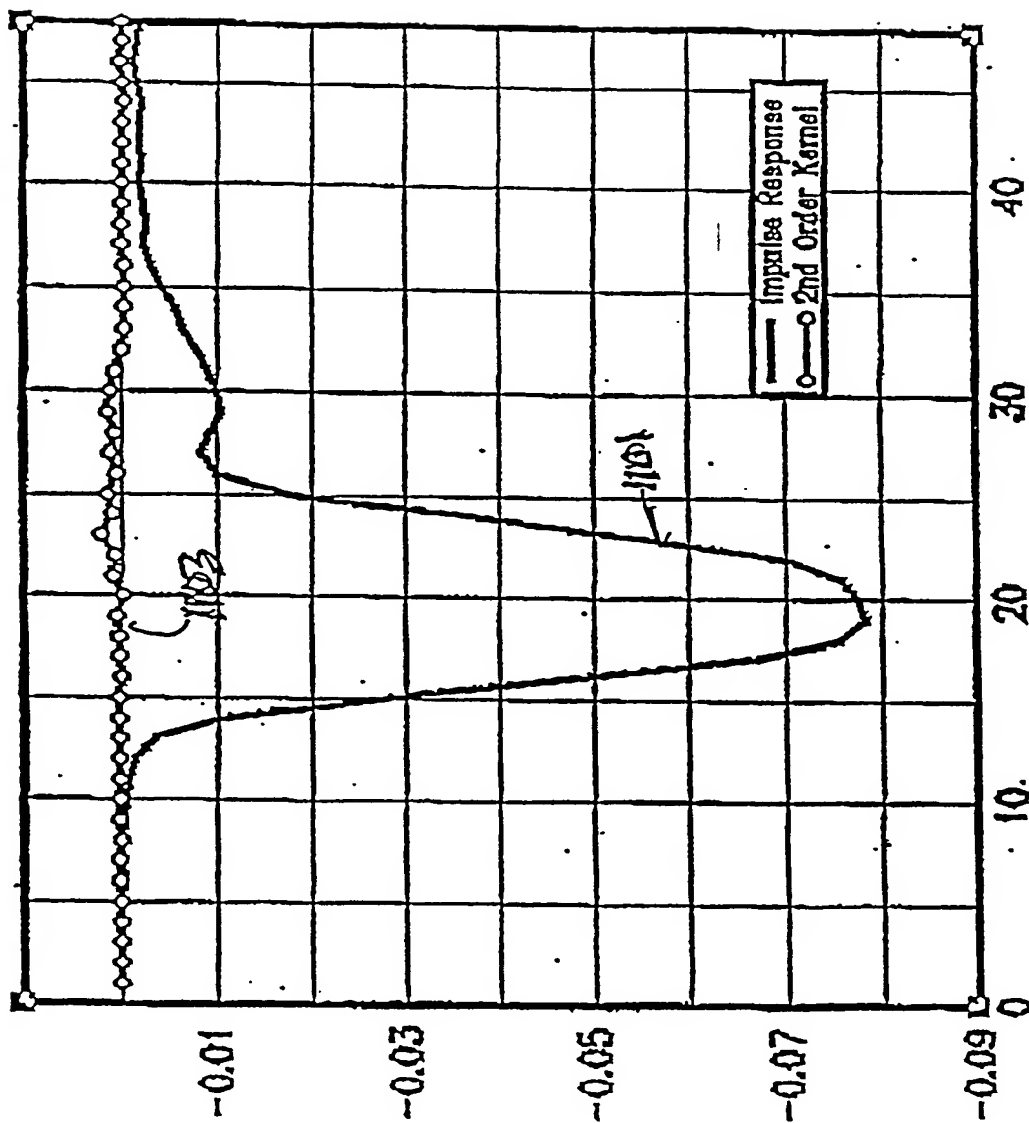


Figure 11

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FIBER	SNR[dB] (linear model)
F0	28.2
F1	26.6
F2	26.7
F3	27.4
F4	28.7
F5	28.2

NOTE: SNR is defined as  $10 \log_{10}(\text{Signal Power/Error Power})$ , and it does not necessarily coincide with the slicer SNR of a receiver

*Figure 12*

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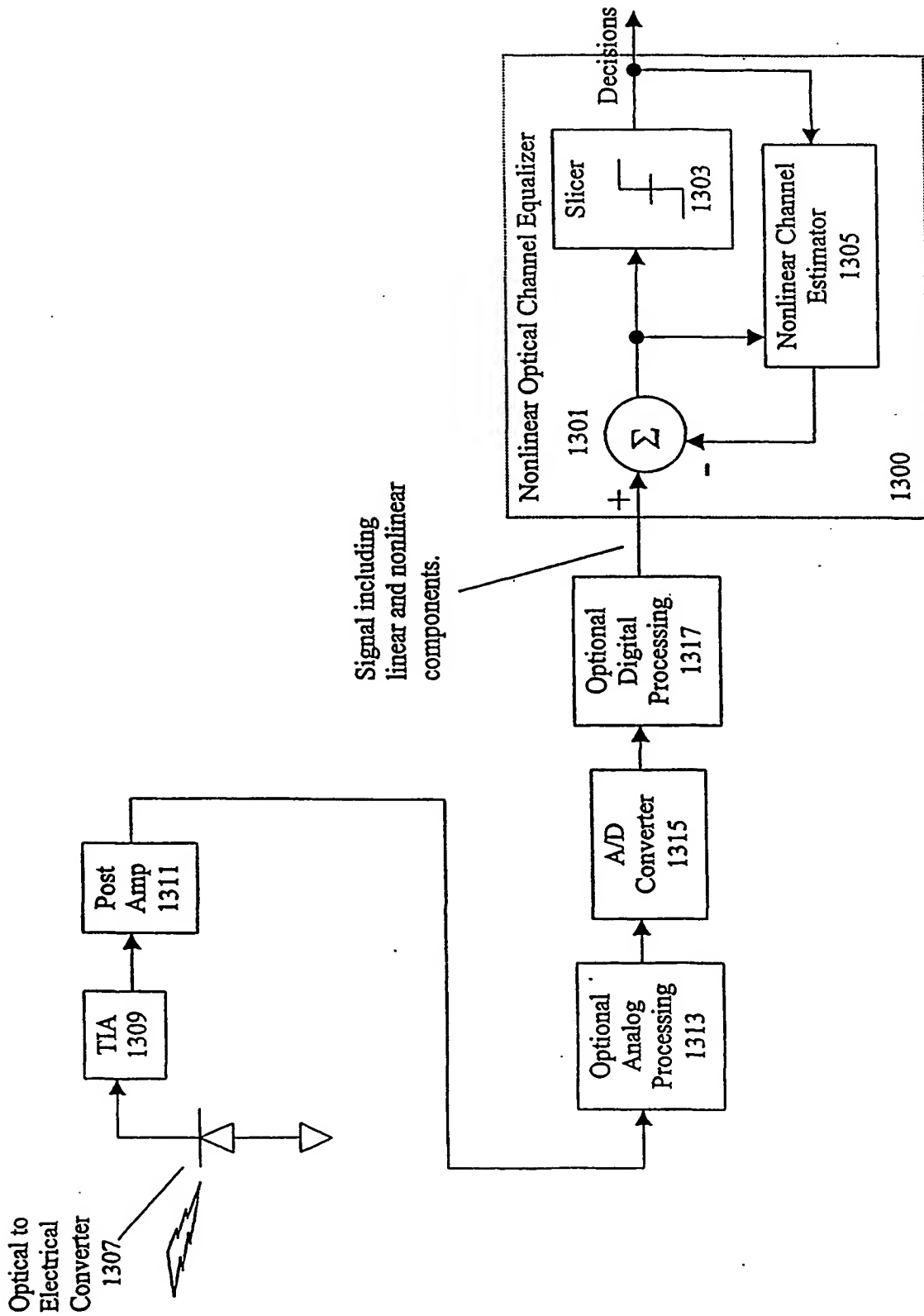


Figure 13

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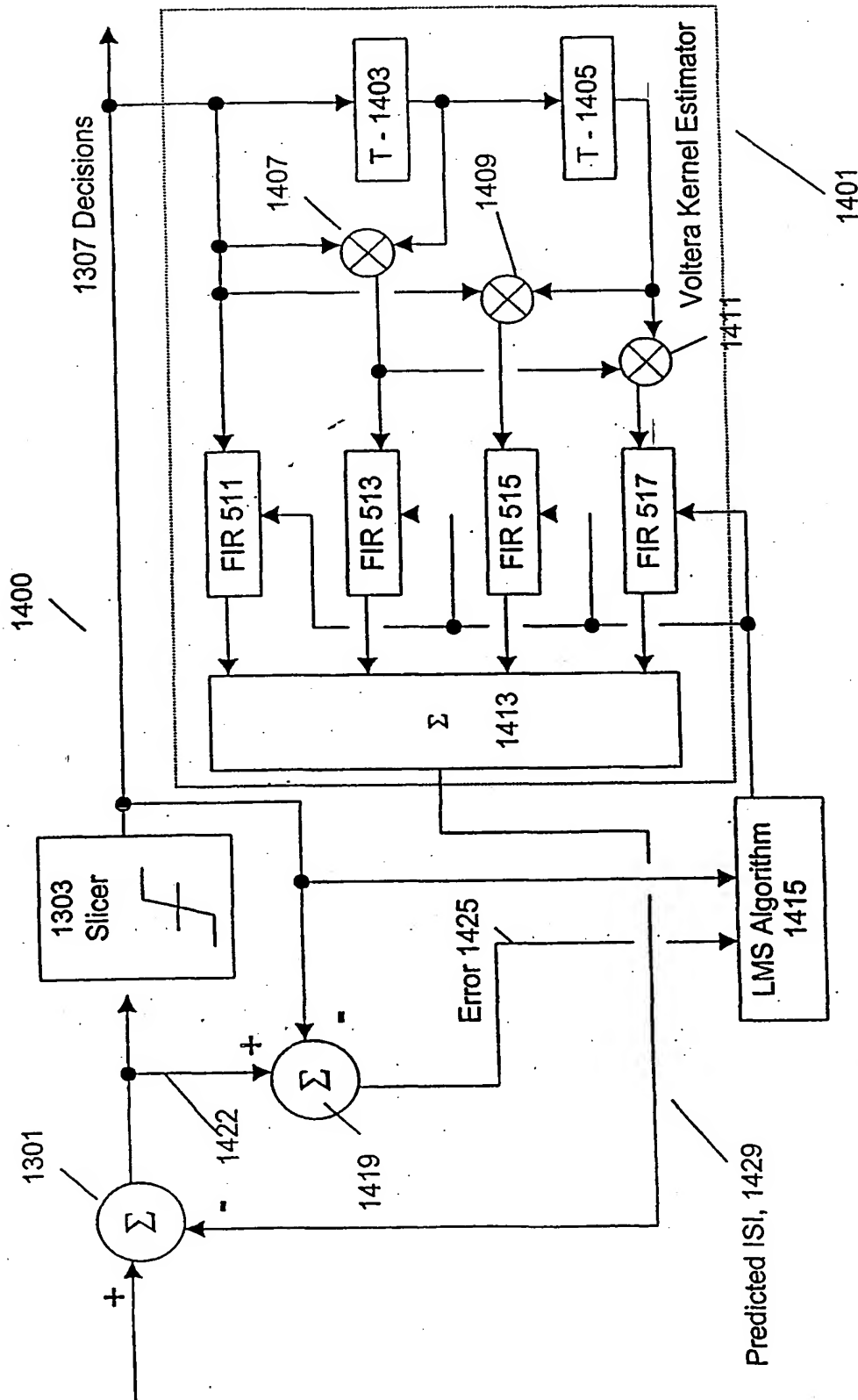


Figure 14A

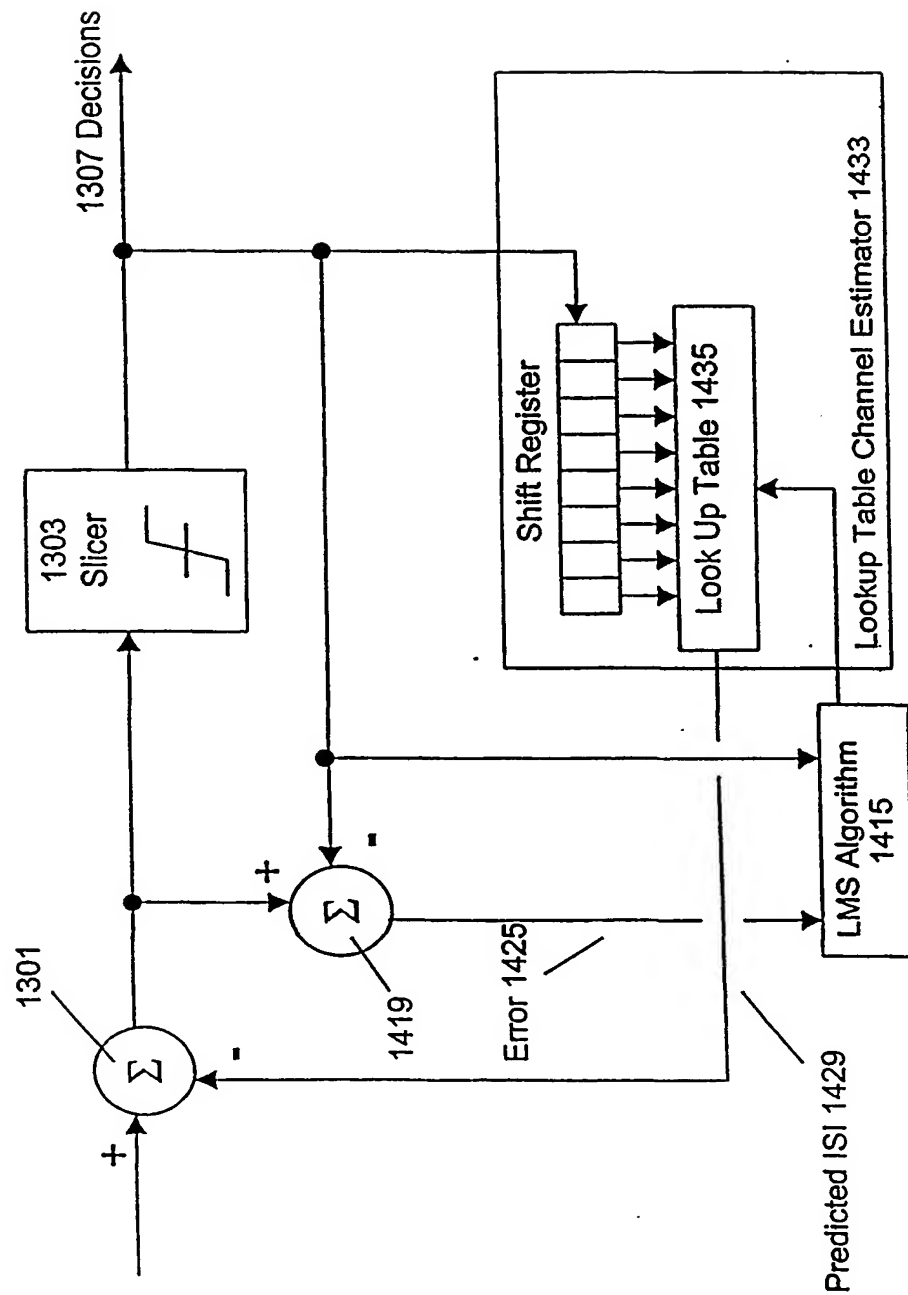


Figure 14B

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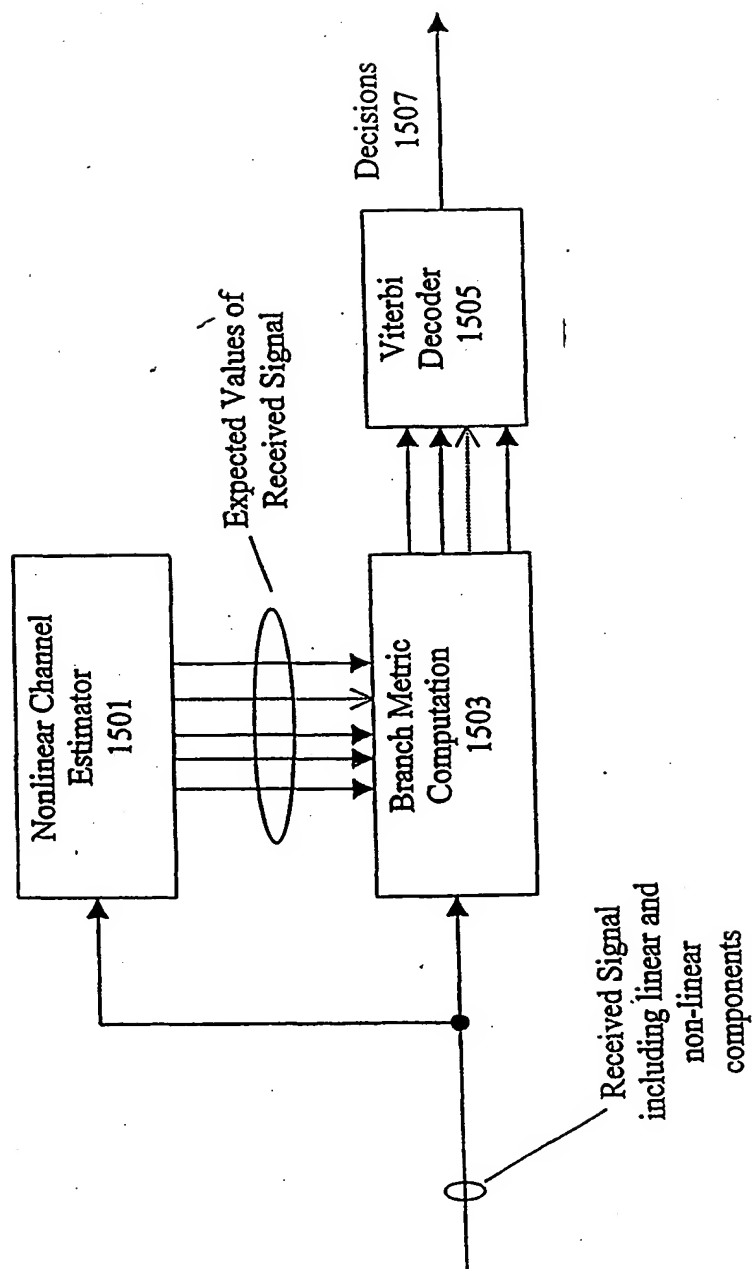


Figure 15





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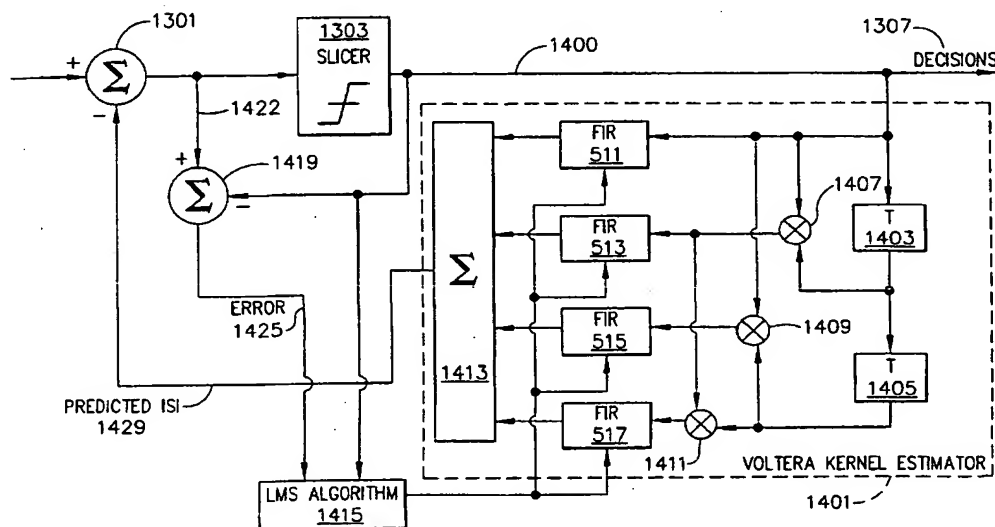
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(54) Title: METHOD AND APPARATUS TO IDENTIFY AND CHARACTERIZE NONLINEARITIES IN OPTICAL COMMUNICATIONS CHANNELS



(57) Abstract: A method for identifying and modeling nonlinearities in communications channels, particularly optical communication channels. A channel in general is modeled as a summation of linear and non linear terms having memory. The terms are functions of the input to the channel with respect to time, such as a sequence of input bits to the channel. In one embodiment the most recent 5 input bits to the optical channel are used to access a value in a look up table. The value accessed is then compared to an actual value received from the channel. The difference between the value in the table and the actual channel value may be used to correct the value in the table, for example using a LMS (Least Means Squared) algorithm. When the look up table and the channel converge the look up table contains a model of the channel with memory that can model nonlinearities.

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## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	BELLINI S ET AL: "Nonlinear cross talk cancellation for high density optical recording" CONFERENCE PROCEEDINGS ARTICLE , 1999, XP010373681 the whole document	1-29, 37-39, 43-45, 47,48
Y		30-36, 40-42, 46,49,50
Y	US 5 726 965 A (HAJJAR ROGER A ET AL) 10 March 1998 (1998-03-10)  abstract; claim 1; figure 4  -/--	30-36, 40-42, 46,49,50

☒ Further documents are listed in the continuation of box C.☒ Patent family members are listed in annex.

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
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X	<p>THORMUNDSSON T ET AL: "Cancellation of nonlinear intersymbol interference in voiceband communication channels" COMMUNICATIONS, COMPUTERS AND SIGNAL PROCESSING, 1997. 10 YEARS PACRIM 1987-1997 - NETWORKING THE PACIFIC RIM. 1997 IEEE PACIFIC RIM CONFERENCE ON VICTORIA, BC, CANADA 20-22 AUG. 1997, NEW YORK, NY, USA, IEEE, US, 20 August 1997 (1997-08-20), pages 862-865, XP010245109 ISBN: 0-7803-3905-3 page 862, column 2, line 27 - line 60; figures 1,2 page 863, column 1, line 53 - line 62 page 863, column 2, line 56 -page 864, column 1, line 73 page 864, column 2, line 16 - line 39 ----</p>	1-29, 37-39, 43-45, 47,48
X	<p>SANDS N P ET AL: "Non-linear identification on the digital magnetic recording channel" SIGNALS, SYSTEMS AND COMPUTERS, 1991. 1991 CONFERENCE RECORD OF THE TWENTY-FIFTH ASILOMAR CONFERENCE ON PACIFIC GROVE, CA, USA 4-6 NOV. 1991, LOS ALAMITOS, CA, USA, IEEE COMPUT. SOC, US, 4 November 1991 (1991-11-04), pages 6-10, XP010026261 ISBN: 0-8186-2470-1 abstract paragraph 'INTRODUCTION! paragraphs '02.6!', 'ADAPTIVE!', 'IDENTIFICATION! paragraph 'CONCLUSION! -----</p>	1-29, 37-39, 43-45, 47,48

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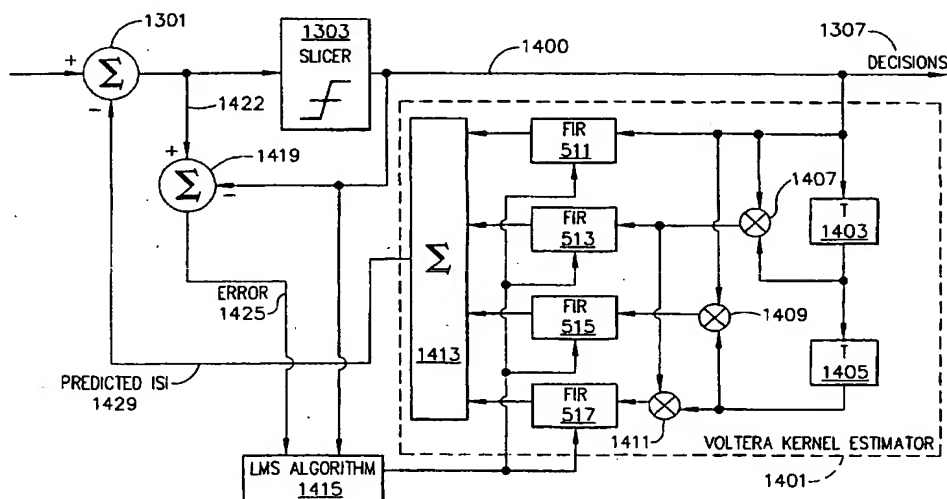
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# METHOD AND SYSTEM TO IDENTIFY AND CHARACTERIZE NONLINEARITIES IN OPTICAL COMMUNICATIONS CHANNELS

## FIELD OF THE INVENTION

The invention relates to methods used to characterize communication channels and, in particular embodiments, to methods used to characterize and model nonlinear optical communication channels.

## BACKGROUND OF THE INVENTION

Signal distortion in an optical channel may be caused by nonlinearities that exist in various components, which comprise an optical channel. Such distortion can be characterized by mathematical models of the nonlinear behavior of the optical communication channel. By using such models, compensatory measures, for example equalizers that compensate for distortion, which degrades the performance of the channel, may be designed.

One source of distortion is dispersion. Dispersion may be a combination of linear and nonlinear components.

Dispersion found in optical fibers, particularly multimode fibers, may limit the bandwidth in optical channels. The problem of dispersion may be more acute in multimode fibers in general, but it may also be a problem in single mode fibers, especially in long runs of fiber. Single mode fibers commonly have lower dispersion than multimode fiber. The dispersion commonly found in single mode fibers may be chromatic dispersion or polarization mode dispersion. The dispersion that is seen in single mode fibers is generally a lot less per length than the dispersion found in multimode fibers. Dispersion is cumulative, however, and so tends to increase as fibers increase in length. Accordingly, methods discussed herein in terms of multimode fibers may apply equally well to single mode fibers.

In multi-mode fibers, the multiple modes of propagation within the fiber commonly cause dispersion. Generally, in the various modes of propagation within a fiber, the light signal has different speeds of propagation. So if a light pulse is sent from a transmitter, the pulse will propagate in multiple modes traveling at different speeds. The pulse, traveling in each mode, will reach the receiver at a different time. The multiple times of arrival of the input pulse traveling in several modes create a distorted pulse, somewhat like a spread out version of the transmitted pulse.

Optical channels are inherently nonlinear. Electromagnetic fields can be described by Maxwell's equations, which are linear. Because Maxwell's equations are

1 linear, the principle of superposition applies to the electromagnetic field. What is  
modulated, however, in optical channels is not the electromagnetic field per se, it is the  
optical power. Superposition doesn't exactly apply to optical power.

5 An optical photo detector is commonly a square law device. The photodetector  
responds linearly to the optical power, in fact the photo current generated by a  
photodetector is commonly a very accurately linear function of the optical power, but the  
power is a quadratic function of the electromagnetic field, thus creating a source of  
nonlinearity.

10 It has been shown that if a laser has a large spectral width, instead of being a  
very monochromatic laser, the significant spectral width tends to result in a linearization  
of the channel even considering the effect of the optical power and the square law  
nature of the photodetector. In other words if a laser has a very monochromatic, narrow  
spectrum then the channel tends to behave less linearly than does a laser that has a  
wider spectrum.

15 Nonlinear behavior in an optical channel may depend to varying extent on the  
properties of the photodetector and the fiber. Additionally there is a possibility of  
distortion from the laser itself. If there is dispersion in the laser, for example because  
the laser has some bandwidth limitation itself, then nonlinearity of the laser could also  
contribute to the total nonlinearity in the optical channel.

20 When the intensity of an optical signal is high, a fiber optic which transmits the  
optical signal itself may introduce nonlinearities. These nonlinearities may result from  
the fact that the index of refraction of the fiber optic depends, to some extent, on the  
intensity of the optical signal itself. This effect commonly gives rise to nonlinearities  
known as "four-wave mixing", "self-phase modulation", and "cross-phase modulation".  
25 Additional nonlinearities may result from the phenomena known as stimulated Raman  
scattering and stimulated Brillouin scattering. For a more comprehensive treatment of  
nonlinearities, see the text "Fiber-Optic Communication Systems", second edition, by  
Govind P. Agrawal, John Wiley and Sons, 1997, ISBN 0-471-17540-4, which is  
incorporated by reference herein.

30 Although the above sources of nonlinearity in an optical channel are presented  
as examples, other sources may exist. The techniques described in this disclosure may  
be applied to all kinds of nonlinearities regardless of their physical source, as will be  
clear to those skilled in the art.

## 35 SUMMARY OF EMBODIMENTS OF THE INVENTION

In one aspect of the invention, the disclosure illustrates a method for modeling

1 the behavior of a data channel. To create the model, the sequence of data input to the data channel is examined. A portion of the sequence of data input to the data channel is used as an index to a channel model value. Output data from the channel is sampled. A numerical channel model value is compared with the sampled value and  
5 the channel model value is adjusted based on the results of the comparison.

In another aspect of the invention, a method for modeling the behavior of a data channel using Volterra Kernels is illustrated. A sequence of data is provided to the data channel. A part of the sequence of data input to the channel is provided to the Volterra Kernel model of the channel. The Volterra Kernel (VK) model produces a channel  
10 model value. The data values measured from the channel are compared to the VK channel model value and the results used to update the Volterra Kernel model.

### BRIEF DESCRIPTION OF THE DRAWINGS

15 The features, aspects, and advantages of the present invention, which have been described in the above summary, will be better understood with regard to the following description, appended claims, and accompanying drawings where:

Figure 1 is a graphical illustration of an environment in which embodiments of the present invention may be used.

20 Figure 2 is a graphical illustration of an equipment setup, which may be used to characterize optical channels.

Figure 3 is a table listing of fibers, which were measured using the measurement setup illustrated in figure 2.

Figure 4 is a graphic illustration of an example of a system that may be used for channel identification.

25 Figure 5 is a graphical illustration of channel identification based on Volterra Kernels (VK).

Figure 6 is a graph illustrating measurement of a channel having an 850 nanometer VCSEL (Vertical Cavity Surface Emitting Laser) and fiber F0, and comparing the signal measurements to linear and nonlinear channel models.

30 Figure 7 is a graph illustrating the measurement of a channel having an 850 nanometer VCSEL and fiber F0, and comparing the amount of error generated by linear and nonlinear channel models.

Figure 8 is a graph representing an impulse response and a second order Volterra Kernel for an 850 nanometer VCSEL and fiber F0.

35 Figure 9 is a table of the signal to noise ratios computed for linear and nonlinear channel models for a channel operated at a wavelength of 850 nanometers.

1           Figure 10 is a graph comparing linear model, measured signal and error within a channel using a fiber F0 at a wavelength of 1310 nanometers.

          Figure 11 is a graph of the impulse response and a second order Volterra Kernel for a channel using fiber F0 and a distributed feedback (DFB) laser with 1310  
5       nanometer wavelength.

          Figure 12 is a table of signal-to-noise ratios for a linear model of a channel employing 1310 nanometer DFB laser.

          Figure 13 is a block diagram of a nonlinear optical channel equalizer, according to an embodiment of the invention.

10          Figure 14A is a block diagram of a nonlinear optical channel equalizer that employs a Volterra Kernel estimator according to an embodiment of the invention.

          Figure 14B is a block diagram of a non-linear optical channel equalizer employing a lookup table channel estimator, according to an embodiment of the invention.

          Figure 15 is a Viterbi decoder employing a nonlinear channel estimator, according to an embodiment of the invention.  
15

## DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

The listed figures describe and illustrate various aspects of the present invention.

20          Accordingly, Figure 1 is a graphic illustration of an environment in which embodiments of the present invention may be used. The environment illustrated at 101 is an information distribution system, such as may be found, for example, in a computer network accessing a remote database.

          In Figure 1, users 105 are coupled to a server 103. The users then may communicate with remote database 107 using fiber optic 109. Fiber optics may be  
25       used to communicate large amounts of data between points because of their large bandwidth.

          The data rate of optical channels is, in part, limited by nonlinearities in the channel. The term "channel", as used herein, includes the laser, amplifiers that drive the laser, the fiber optic, the photo detector receiver and all elements included in the  
30       transmission and reception of a fiber optic signal.

          For characterizing optical channels, the measurement setup illustrated in Figure 2 was used.

          Figure 2 is a graphical illustration of an equipment setup used to characterize optical channels. A signal is generated by modulating a laser 219. The modulated  
35       laser signal is provided to a fiber optic 215. In the embodiment illustrated in Figure 2, the signal provided to the optical channel was a 1 Gigahertz (GHz), 127 bit, pseudo-

1 random binary sequence provided by bit error rate tester 201. The resulting received  
signal was detected by a photodetector 207, captured using an oscilloscope 205 and  
stored as a file in computer 209. Using computer 209, the received signal may be  
processed and the nonlinearity that exists in the received signal can be identified. The  
5 approach taken is that no attempt is made to identify the source of the nonlinearity as  
belonging to a specific channel component such as a photodetector or laser or any  
other source. Instead the nonlinearity in the received signal was examined without  
being concerned for the physical source of the nonlinearity.

Two types of lasers were tested. The first type was a 850 nanometer VCSEL  
10 (vertical cavity surface emitting laser) and the second type of laser was a 1310  
nanometer DFB (distributed feedback) laser. All measurements were done at a data  
rate of 1 gigabit per second.

The bit error rate data tester 201 generated a pseudo random binary sequence  
that was periodically repeated. The channel measurements were performed at a data  
15 rate of 1 gigabit per second, but the method may be applied to any data rate.

In the setup illustrated in Figure 2 free space optics and an optical bench 221  
were used. The laser was aligned using alignment screws so that the laser 219, the  
fiber 215 and the lens were arranged to focus the light into fiber 215. Laser 219  
requires a DC bias current provided by bias power supply 203. A bias Tee 211 allows  
20 the combination of the data signal with a bias in order to apply a correctly biased data  
signal to the laser 219.

A length of fiber 215 is contained in a spool so that lengthy fibers up to more than  
1 kilometer may be used. In the case of single-mode fibers, the length of the spool  
could exceed 700 km. Photodetector 209 is a commercial unit having a bandwidth of  
25 10 gigahertz. The oscilloscope 205 is a real time sampling oscilloscope which samples  
at 8 gigahertz. Because the data rate used was 1 gigabit per second, the received  
signal was sampled on average 8 times per bit. Samples of the received signal were  
captured in the memory of the oscilloscope and then downloaded to the computer 209  
in the form of a file. Typical received signal data files contained about 65,000 data  
30 points representing received samples of the pseudo random input sequences of 127  
bits.

Once the data points have been accumulated they may be processed and  
information about the behavior of the optical channel, particularly the nonlinearity, may  
be extracted. Additionally any possible nonstationarity of the channel may be identified.  
35 In other words, if the channel changes in time, such nonstationarity may be detected.  
In the measurements taken, however, no significant nonstationarity was observed.

1           Figure 3 is a table listing of fibers, which were measured using the measurement  
setup illustrated in figure 2. Six different fibers, having core diameters from 50 to 62-1/2  
microns and the lengths from 270 meters to about 2.2 kilometers, were tested. All of  
the fibers exhibit some dispersion phenomenon and bandwidth limitation to varying  
5           extent.

To model channel nonlinearity two different mathematical methods, representing  
nonlinear functions having memory, were chosen. Because dispersion is inherently  
a function having memory, the resulting channel nonlinearity is a nonlinear function with  
memory, as opposed to memoryless nonlinearity. Memoryless nonlinearity may be  
10           represented by a function of the form  $Y = F(X)$ , with the nonlinearity an arbitrary  
nonlinear function  $F$  of a single variable. Nonlinearity with memory can be described  
as a nonlinear function of a number of consecutive samples of the transmitted data, so  
that the nonlinear function with memory is of the form  $Y = F(X_n, X_{n-1}, X_{n-2}, \dots)$ . In other  
words nonlinearity with memory is a function of several variables, where the variables  
15           are exemplarily samples of the transmitted bit sequence. Nonlinearity with memory is  
a more general kind of nonlinearity that may be found in optical channels. In other  
words the characteristic of an optical channel is not only a function of the current bit, but  
depends also on previously transmitted bits.

The nonlinearity in an optical channel can be modeled as a look-up table, for  
20           example as a nonlinear function of the five most recently transmitted bits. In a digital  
transmission system the transmitted bits have 2 levels, 0 and 1 (or +1 and -1 depending  
on the convention that is used). Because of the discrete nature of the transmitted bits,  
the function characterizing a channel depending on the five most recent bits can only  
have  $2^5=32$  values. Accordingly there are 32 possible values that model the channel  
25           by listing all the values for all the possible sequences of the most recent 5 input bits.  
Such a model can be implemented as a look-up table. The look up table is one model  
with memory for characterizing an optical channel having nonlinearity.

A second optical channel model is based on a Volterra series. Volterra series  
have been studied in mathematics for a considerable time. Volterra series are a way  
30           to represent nonlinear functions. In general Volterra series are infinite series, i.e. a  
series with infinite number of terms. In the present case, however, since the transmitted  
data is binary, the number of terms is finite. The number of terms in the series used to  
model a binary optical channel is 2 to the power  $N$ , where  $N$  is the number of most  
recent transmitted bits, which are taken into account. That is the same number of terms  
35           as the number of entries in a look-up table. Accordingly, no matter what description is  
used, whether the look-up table approach or the Volterra series approach, the number

1 of required elements in each model is 2 to the power N, where N is the number of most recent bits transmitted that are taken into account. In the look-up table approach the 2 to the N parameters are the values of the channel for all the possible values of the most recent N input bits.

5 For the Volterra series, the parameters are the coefficients of the series and because the series has  $2^N$  terms there are  $2^N$  coefficients.  $2^N$  is the same number of parameters as required by the look up table model. Accordingly regardless of which description is chosen, the maximum number of parameters that is needed to completely specify the nonlinear function is the same, i.e.  $2^N$ . It can be shown that the Volterra  
10 Kernel representation is mathematically equivalent to the look-up table. In fact a mathematical transformation known as the Hadamard transformation can transform the look up table model to the Volterra Kernel model and Volterra Kernel model to the look up table model.

N is generally an empirically determined value, the exemplary value of N=5 in the  
15 present embodiment appears to work very well. The value of N, of course could depend on the fibers, wavelength of the laser and the rate of the data being transmitted. In principle it is possible to find fibers where N is larger or smaller, but in present embodiments N=5 is sufficient.

An advantage of choosing the Volterra series description is that there is a way to  
20 make the description somewhat compact by grouping terms. By grouping the terms  $2^N$  terms are transformed into  $2^{(N-1)}$  convolution-like terms having a shift register-type sequence. That means, for example, the terms that go into the sequence of grouped terms are products of bits. So, for example, a  $X_N$  term would be multiplied by an  $X_{N-1}$  term and so on. The shift register sequence of grouped terms means shifted versions  
25 of the product. So, for example, this shift register sequence would be in the form  $X_N * X_{N-1}$ ,  $X_{N-1} * X_{N-2}$ ,  $X_{N-2} * X_{N-3}$  and so on. This is shift register-type sequence is one that can describe terms of the Volterra series as a convolution of this kind of shift register-type sequence with a certain kernel. A kernel is an element that resembles an impulse response. A kernel is not an impulse response in the traditional sense, but a traditional  
30 impulse response is used as a linear portion of the nonlinear kernel function.

Terms involving a convolution of a shift register type sequence with a certain kernel, are referred to as Volterra Kernels. There are multiple Volterra Kernels corresponding to different kinds of products of bits. The maximum number of Volterra Kernels needed to represent an N bit sequence to is  $2^{N-1}$ . So, for example, in the case  
35 where N=5, the total number of terms in the Volterra series is  $2^N$  or 32 terms. But these 32 terms can be mapped into 16 Volterra Kernels. Sixteen Volterra Kernels suffice and

1 the number of Volterra Kernels is equal to  $2^{(N-1)}$ , or in the present example  $2^4$  or 16. So  
there are 16 Volterra Kernels and the Volterra Kernels may provide a more convenient  
and more compact description of a nonlinearity particularly because commonly in many  
applications the number of Volterra Kernels is actually less than  $2^{(N-1)}$ . Although the  
5 number of Volterra Kernels to theoretically define a Volterra Kernel model is  $2^{(N-1)}$ , some  
of the kernels are very small and can be neglected. In some situations the channel may  
be effectively modeled by one or two Volterra Kernels. That is the situation in the  
optical channels of the present embodiment. In present embodiments the nonlinearity  
is simple enough so that it can be described completely by a linear term and a single  
10 Volterra Kernel, indicating that a fairly simple kind of nonlinearity is present.

Because the nonlinearity is simple doesn't mean that its negligible. In fact in  
present embodiments the nonlinearity, though simple, is a very strong. Because the  
nonlinearity has a simple description, simple equalizers may be built. In other words  
nonlinear equalizers with memory which are relatively simple but very powerful may be  
15 built. Such equalizers can be very effective because they can deal with the nonlinearity  
that is strong whereas a traditional kind of linear equalizer might fail completely.

Figure 4 is a graphic illustration of an example of a system that may be used for  
channel identification. The system is implemented in software.

Input bits 401 are provided to a channel 403. What is used for the channel 403  
20 is the measurements that were taken with the setup illustrated in Figure 2. So the  
channel input and channel response are actual measured values.

In the present embodiment the measurements are stored in a file and then  
processed off-line in a computer using a software program that implements the  
remainder of the system illustrated in Figure 4. This was done for the sake of  
25 convenience because the equipment for the setup in Figure 2 was readily available.  
There is however no constraint to prevent the present disclosed methods from being  
implemented as part of a real time or embedded system.

The look-up table 409 is adaptive. That is the value in it can be adapted using  
the LMS (least-means-squared) algorithm. Basically what is done is to compare the  
30 measured sequence from the channel 403 (the file of received values stored by  
computer 209) with the output of the look-up table. The addresses in the look up table  
409 are received from a shift register 407 representing the values of the latest 5 input  
bits provided as input to the channel. Initially the look-up table values are initialized to  
all zeros started from situations where there is no knowledge of the nonlinearity. In  
35 such a case the error will be equal to the input signal. So the error will be large initially.  
The values in the look up table can be adjusted using an LMS algorithm to update the



1 look-up table according to the error 405 observed. The LMS algorithm will converge so that it tends to drive the error to zero or as close as possible to zero.

Once the look-up table converges the error will be small or zero. In actual practice the error may not be exactly zero because the input signal may include some random noise. Additionally it is also possible the look-up table doesn't perfectly model all the nonlinearity. There may be some residual unaccounted for nonlinearity because N was chosen equal to 5 but in practice a N of 8 or 10 may have been required to more closely model the fiber. The choice of N is an implementation detail depending on the type of fiber, data rate, and a variety of other factors.

10 Additionally in figure 4 the look up table is like having an array where the address is created by looking at 5 consecutive bits, but the number is accessed is a single number that could be represented by multiple bits which could be 16 bits or 24 bits, and as such may contain some quantization error.

Figure 5 is a graphical example of channel identification based on Volterra Kernels. The Volterra Kernel approach is an approach mathematically equivalent to the use of a look-up table, as illustrated in Figure 4. In Figure 5, four Volterra Kernels are used. Normally there would be 16 Volterra Kernels present in a case where N is equal to 5. In some cases some of the Volterra Kernels may be negligible and depending on the Bit Error Rate (BER) required only the most important ones may need to be taken into account in the model, as for instance illustrated in Figure 5. For example in Figure 5 there is a linear term which is represented by the Kernel labeled FIR 511. "FIR" indicates that each Kernel is represented by a finite impulse response (FIR) filter. In Figure 5, FIR 511 directly takes a sequence of input bits and creates a convolution of the input sequence with an impulse response of FIR filter 511. Hence FIR 511 is a linear term, i.e. a traditional convolution. So if only a term represented by FIR 511 is needed for the channel model, the channel is essentially linear. If, in addition to FIR 511, other terms are present then the model is nonlinear.

FIR 513 is a Volterra Kernel which is associated with products of two consecutive bits, i.e. a second order Volterra Kernel. FIR 513 is a second order Volterra Kernel because it accepts a term 505 which is a product of the most recent input bit and the bit preceding the most recent input bit. The most recent input bit is designated as  $A_N$  and the bit preceding the most recent bit is designated  $A_{N-1}$ .

Second order Volterra Kernel FIR 513 is associated with two (consecutive) bits i.e. bits that are one time delay apart, it accepts the product of two (consecutive) bits. Another second order Volterra Kernel 515 is produced by taking the product of bits that are two time delays apart, 501 and 503 representing time delays. The most recent bit

1 and the bit prior to the second most recent bit are multiplied and result in output 507,  
which is the accepted by FIR 515. In other words  $A_N$  is multiplied by  $A_{N-2}$ , here, because  
this is delayed by 2 units. FIR 515 is a Finite Impulse Response filter (just as FIR 511  
and FIR 513) but the input, instead of being bits is the product of 2 bits, and so it is a  
5 second order Volterra Kernel. FIR 515 accepts the product of bits  $A_N$  and  $A_{N-2}$ , so it is  
a different type of Volterra Kernel than FIR 513 that accepts sequential bits. Both FIR  
515 and FIR 513 are second order.

A third order Volterra Kernel FIR 517 is determined by the product (509) of 3 bits.  
509 is a product of 3 consecutive bits  $A_N$ ,  $A_{N-1}$  and  $A_{N-2}$ . Accordingly FIR 517 is a third  
10 order Volterra Kernel.

In the simplified model illustrated in Figure 5 only the aforementioned 4 kernels,  
the linear kernel, two second orders kernels, and a third order kernel are present. In  
practice, if a nonlinearity were very strong, the Volterra Kernel model could have 16  
kernels or more if N greater than 5 (where N is the number of most recently transmitted  
15 bits to be considered). In the present embodiment out of the 16 Volterra Kernels only  
the four illustrated in Fig. 5 are significant, the others are negligible.

In the present embodiment FIR 511 and FIR 513 are much more significant than  
FIR 515 and FIR 517, and in fact FIR 515 and FIR 517 could be completely neglected.

The Volterra Kernel model tends to simplify the description of the channel  
20 because it reduces the number of independent terms that need to be taken into  
account. Volterra Kernels may group together all the terms that are time-shifted  
versions of each other. In the more general Volterra Series description, all the terms  
are represented independently. When groups of terms of a Volterra Series are time-  
shifted versions of each other, they may be associated with each other, and all the ones  
25 that are time-shifted versions of each other may be grouped as a single Volterra Kernel.

The two equivalent representations - the look-up table model and the Volterra  
Kernel model are mathematically equivalent because the Hadamard transformation can  
transform one into the other. The reason to choose one or the other is essentially ease  
of implementation. The model that is simpler is commonly dependent on the particular  
30 problem that is trying to be solved. For example, if a strongly nonlinear function with  
short memory is present (meaning small amounts of dispersion) the look-up table  
probably provides a simpler model. The look up table is likely simpler because, if the  
dispersion is not large N will not be large. If N is not large then  $2^N$  is not a very large  
number of coefficients. But if the memory span of the nonlinearity (i.e. N) grows then  
35 the look-up table grows exponentially because the size of the look-up table is  $2^N$ . The  
size of the look up table may become prohibitively complex for large N. In some cases

1 Volterra Kernels may provide a simpler model when  $N$  is large and the nonlinearity has a simple form which can be described with few kernels, such as the previous example that could be limited to two kernels.

5 If  $N$  is large, it will generally indicate that there is a lot of dispersion in the channel, but the form of the nonlinear function could be very simple. The function may be simple enough that it can be described, as in the previous example, by only two Volterra Kernels. If  $N$  is large and the Volterra model is simpler, the nonlinearity may be completely modeled with two kernels, even though  $N$  is very large. Accordingly in some cases the Volterra Kernel description is simpler. In other cases the look-up table  
10 description is simpler.

In the studies performed, the amount of dispersion necessitated an  $N$  on the order of 5, but in principle, for severely bandwidth limited fibers,  $N$  could be larger. In the case where two Volterra Kernels are sufficient to create an accurate channel model, regardless of how large  $N$  is, the Volterra Kernel description is generally simpler.

15 Figure 6 is a graph illustrating channel measurement, of a channel having an 850 nanometer VCSEL laser and fiber F0, and comparing the signal measurement with linear and nonlinear fiber models. In Figure 6 the solid line corresponds to the observations, the dotted line represents the linear model, and the dashed and dotted represents the nonlinear model. As can be seen from 601, 603 and 605 the nonlinear  
20 model approximates the measurements of the channel to a greater degree than the linear model. Accordingly if the channel model were limited to a linear model a good fit for the transmitted data would not be achieved. In contrast using the nonlinear model a significantly closer fit may be obtained.

25 Figure 7 is a graph illustrating channel measurement of a channel having an 850 nanometer VCSEL laser and fiber F0, and comparing the signal measurement with amount of error generated by linear and nonlinear channel models. Figure 7 is a graph representing the same time as the graph of Figure 6 except that the errors instead of the signals themselves are shown. In Figure 7 the linear model error is represented by the lines with circles and the nonlinear model is represented by the dotted line. As can  
30 be readily appreciated, by observing the nonlinear model points at 701 A, B, and C and comparing it with the linear model points at 703 A, B, and C the nonlinear model achieves a significantly smaller error.

35 Figure 8 is a graph representing the impulse response and a second order Volterra Kernel for a channel having an 850 nanometer wavelength VCSEL laser and utilizing fiber F0. Figure 8 illustrates an impulse response (the linear term of the overall response) at 801. Figure 8 also illustrates the response of the second order Volterra

1 Kernel at 803. In the present embodiment, the second order Volterra Kernel, which is  
associated with products of two consecutive bits, is the only significant nonlinear kernel.  
So the response of the second order Volterra Kernel generated from the product  $A_N \times$   
5  $A_{N-1}$ , i.e. FIR 513 in figure 5. FIR 511 corresponds to the linear kernel response 801  
and FIR 513 corresponds to the second order response 803. Using just the Volterra  
Kernels of FIR 511 and FIR 513 a close approximation of the channel which includes  
nonlinear elements and memory was achieved. The same method was used to  
examine the remaining fibers in the table of Figure 3. The signal-to-noise ratio for the  
10 linear model and for the nonlinear model (which was a linear model with nonlinear  
addition) was computed for each fiber.

Signal-to-noise ratio is defined as 10 times the base 10 log of the signal power  
divided by the error power. To compute the signal-to-noise ratio the power for the  
signal was computed. The sum of the squares of the samples of the signal yields the  
total power of the signal and the sum of the squares of the samples of the error yields  
15 the error power.

There are two versions of the error power, one of them for the linear model  
containing one Volterra Kernel and the other for the nonlinear model containing the  
additional nonlinear Volterra Kernels. The result of the error computations for the linear  
and the nonlinear model is illustrated in the table of figure 9. As can be seen from the  
20 table of figure 9 the signal-to-noise ratio for the linear model is in the range of 12 to 13  
dB. In the nonlinear model the error is significantly smaller, and correspondingly the  
signal to noise ratio is significantly higher in the range of 23 to 25 dB. The nonlinear  
model yields a model having approximately a 10 to 13 dB better signal to noise ratio,  
which is a significant improvement.

25 The previously described measurements were all done at 850 nanometers  
wavelength. In the measurements taken, the nonlinearity was much larger at 850  
nanometers than at 1310 nanometers. If the same measurements are repeated at  
1310 nanometers, the linear model appears to be very adequate.

Figure 10 is a graph of measured signal vs. linear model and the error between  
30 the measured signal and the linear model. Accordingly with the present data rate and  
fibers the linear channel model at 1310 nanometers appears to be fairly accurate. The  
graph of figure 10 illustrates the measured signal as a solid line. The graph of figure  
10 is the result of a linear model shown as the line with circles. The line with diamonds  
represents the error.

35 Figure 11 is a graph of the impulse response and a second order Volterra Kernel  
for the channel comprising fiber F0 and a DFB laser having a 1310 nano-meter

1 wavelength. The impulse response is illustrated at 1101 and the second order Volterra Kernel is illustrated at 1103. The second order Volterra Kernel is almost zero and most likely would not have to be taken into account in a model of the channel.

5 Figure 12 is a table of signal-to-noise ratios for a linear channel model having a DFB laser operating at a wavelength of 1310 nanometers. All of the channel signal to noise ratios of all measured channels operating at a wavelength of 1310 nanometers were in the range of 26 to 28 dB indicating that a nonlinear term may not be necessary at a wavelength of 1310 nanometers, for a one gigahertz data rate.

10 Additionally measurements were done including cases where mechanical motion of a fiber was introduced during the measurement process to examine motion induced nonstationarity of the general response. These observations for nonstationarity were done because there is some belief that the optical channel is not fixed in time and if vibration is introduced in the fiber some redistribution of the modes in the fiber may change the response of the fiber and accordingly the channel may be time-dependent.  
15 No evidence of any significant change in the fiber response as a result of motion was observed.

Slow changes in the channel may be compensated by the LMS algorithm adjusting the channel model to track those types of changes.

20 A program listing of a computer program used for the channel studies is included as Appendix A. Essentially, the program takes an input block of data from the measurements processes it, and then trains the canceller. It then computes the Volterra Kernels coefficients of the model using the linear model or the nonlinear model. The program computes a signal to noise ratio and it prints out the results.

25 Figure 13 is a block diagram of an optical receiver including a nonlinear optical channel equalizer. The nonlinear optical channel equalizer 1300 accepts a signal which includes linear and nonlinear components.

30 The electrical signal commonly results from converting an optical signal to the electrical domain using an optical to electrical converter 1307, such as for example a PIN diode, avalanche photodetector (APD), or another detector. The optical to electrical converter signal is amplified using a transimpedance amplifier (TIA) 1309 and a postamplifier 1311. The postamplifier 1311 generally should not hard-limit a signal provided to it as hard limiting may introduce nonlinearity.

35 After processing the signal provided to it the postamplifier 1311 may provide a processed signal to an optional analog processing block 1313. The analog processing block 1313 may provide such analog processing as filtering and automatic gain control, prior to providing an output signal to an analog to digital converter 1315. The output

1 signal from the analog to digital converter converts the electrical signal provided by the  
optional analog processing block 1313 to a multibit digital representation, prior to  
providing the multibit digital representation to a nonlinear optical channel equalizer  
1300. The nonlinear optical equalizer 1300 operates in the digital domain, and may be  
5 implemented using special-purpose digital logic or a general purpose programmable  
digital signal processor. Prior to entering the nonlinear optical equalizer 1300 the  
multibit signal may undergo additional preprocessing steps such as filtering, linear  
equalization, interference cancellation, etc. in an optional digital processing block 1317.  
Equalizer 1300 is a decision feedback equalizer comprising a detector such as slicer  
10 1303, a compensator such as subtractor 1301 and a feedback block 1305. The  
feedback block 1305 includes a nonlinear channel estimator employing a lookup table  
as illustrated in Figure 4 or the Volterra Kernel approach as illustrated in Figure 5. A  
difficulty with using the look up table approach of Figure 4 or the Volterra Kernel as  
illustrated in Figure 5 is that in both cases the Volterra Kernel or look up table  
15 coefficients need to be identified. One solution to the problem of coefficient  
identification is to have the transmitter send a training sequence, which is known a  
priori, to the receiver. The nonlinear channel estimator 1305 can then be trained using  
the known training sequence. In such a case, the functioning of the nonlinear channel  
estimator 1305 would proceed as in Figure 4 or Figure 5 as the bit sequence would be  
20 known and differences produced by the channel could be readily identified.

In practice, a training sequence may not be required because the decisions 1307  
of the decision feedback equalizer 1300 and the nonlinear channel estimator 1305 may  
still converge. Initially, because the channel estimator 1305 is not trained, the decisions  
1307 will have multiple errors. There is however, in most channels, a bias towards  
25 good decisions. Most decision feedback equalizers will converge if the channels do not  
exhibit excessive intersymbol interference (ISI). Accordingly, if the coefficients in the  
nonlinear channel estimator 1305 are incorrect initially, there are both good and bad  
decisions. As long as the good decisions outnumber the bad decisions, there will be  
a converging trend and the nonlinear channel estimator 1305 will eventually tend to  
30 converge.

The nonlinear channel estimator 1305 may also be trained using an LMS  
algorithm as illustrated in Figure 4 or 5. As the coefficients begin improving in the  
nonlinear channel estimator 1305, the improvement helps make a larger percentage of  
correct decisions, which further assists in the convergence of the nonlinear channel  
35 estimating filter 1305. Once the values in the estimating filter converge, the nonlinear  
channel estimator 1305 will have modified the coefficients so that essentially all correct

1 decisions are made. Any incorrect decisions made by the system tend to corrupt the  
values in the nonlinear channel estimator 1305, however, as long as the correct  
decisions outnumber the incorrect decisions the nonlinear channel estimator will  
converge to an essentially correct solution. In other words, as long as the majority of  
5 decisions are correct the coefficients of the nonlinear channel estimator 1305 will have  
a net movement in the correct direction and converge.

Once there is an initial convergence in the nonlinear channel estimator 1305 the  
signal to the slicer 1303 is improved because at least some of the intersymbol  
interference is cancelled in summation unit 1301. As a result the number of correct  
10 decisions 1307 increases which leads to a better channel estimation. Past decisions  
are stored within the nonlinear channel estimator 1305 and are used to compute a  
replica of the intersymbol interference in order to provide it to summation unit 1301.

If a Volterra Kernel structure similar to Figure 5 is used for the nonlinear channel  
estimator then the memory of past decisions are stored in the FIR filters 511 through  
15 517, which each nominally contain a FIR delay line structure. If the look up table  
approach is used then the memory for the past decisions are stored within a shift  
register, such as that illustrated in 407 at Figure 4.

Figure 14A is a block diagram of an exemplary nonlinear channel equalizer as  
may be used in the nonlinear decision feedback equalizer of Figure 13. The nonlinear  
20 channel estimator Figure 14 is similar to the Volterra Kernel model illustrated in Figure  
5. The Volterra Kernel model of Figure 5 was used as an illustration of characterization  
of the channel. The nonlinear channel estimator illustrated in Figure 14 has an LMS  
update loop similar to Figure 5. Additionally, similar to Figure 5, the number of Volterra  
Kernels employed would depend upon the characteristics of the channel and the laser  
25 used to drive the channel.

In Figure 14A, a signal 1427, which has been provided from an optical channel  
and converted to an electrical signal, is accepted by an optical channel equalizer,  
shown generally at 1400. The equalizer 1400 accepts the signal 1427 into a summation  
unit 1301 where a (negated) correction signal 1429, representing the predicted inter-  
30 symbol interference, is added. Prior to the training and convergence of the Volterra  
Kernel estimator correction signal is zero or an arbitrary value. Slicer 1303 makes  
decisions 1307 as to the values of the signal transmitted. Decisions 1307 are accepted  
by Volterra Kernel estimator 1401, which models the nonlinearities of the channel that  
provides the signal to the equalizer 1400. The output of the Volterra Kernel estimator  
35 provides a value of predicted intersymbol interference 1429, which can then be  
subtracted from the accepted signal in order to accurately recreate a transmitted signal

1 which has been transmitted.

The error in the predicted intersymbol interference 1429 is estimated by comparing decisions 1307 from slicer 1303 with the input signal 1422, which has been adjusted in summation unit 1301 by removing the predicted intersymbol interference ISI 1429. The decisions 1307 and error 1425 are used to adjust the FIR filters 511, 513, 515, and 517, which exemplarily illustrate the FIR filters which comprise the Volterra Kernel estimator 1401. In such a manner, the Volterra Kernel estimator may be trained and compensate for non-linearities within the channel that provides the signal to the equalizer 1400.

10 Figure 14B is an exemplary block diagram of a non-linear optical channel equalizer employing a lookup table channel estimator, according to the embodiment of the invention. In Figure 14 B an LMS algorithm may be employed in adjusting the values within the look up table 1435. The system 14B may be operated so that training of the equalizer is accomplished by processing of a signal provided from an optical channel, determining error signals and adjusting the equalizer 1401. In such a manner the equalizer may be trained to model the channel parameters. Those skilled in the art will recognize that the equalizers may be trained by employing a known sequence. Because such a sequence is known a priori the difference between the response of the channel and the desired response of the channel, i.e., the known sequence, can be readily determined. Such sequences may shorten the time necessary to train a nonlinear optical channel equalizer.

20 A nonlinear channel estimator could also be built based on the look up table approach illustrated in Figure 4. The implementation of such a look up table version is a straight-forward adaptation of the channel characterization circuit illustrated in Figure 4.

25 Figure 15 is a block diagram of a nonlinear channel estimator combined with a Viterbi decoder. Instead of a decision feedback equalizer a Viterbi decoder may be used. Nonlinear channel estimator 1501 would be used to compute the expected signal going to the branch metric computations 1503. The remainder of the Viterbi decoder system including the actual Viterbi decoder itself, block 1505, is similar to the linear case. The nonlinear channel estimator 1501 is creating a model of the received signal. If the nonlinear channel estimator 1501 has a memory comprising  $k$  bits, that is it remembers the last  $k$  inputs, then the Viterbi decoder 1505 would have  $2^{(k-1)}$  states. Therefore, if  $k=3$  then the Viterbi decoder 1505 would be a 4 state Viterbi decoder. If the nonlinear channel estimator 1501 has a memory of 3 bits then it can support eight different expected values of the received signal. Which would be implemented with a



1 look up table have eight locations. The expected values of the received signal are used  
by the branch metric computations 1503 to compute all the branch metrics in the Viterbi  
decoder.

5 The Viterbi decoder illustrated in Figure 15 is the same as a standard type Viterbi  
decoder except for the fact that the channel estimator function is a nonlinear channel  
estimator with memory. The nonlinearity is expressed either in the form of a look up  
table or a Volterra Kernel.

10 The Viterbi decoder includes a receiver for receiving a signal including linear and  
non linear components. A non linear channel estimator computes the expected values  
of the received signal. A branch metrics computer computes the branch metrics based  
on the expected values of the received signal. A standard Viterbi decoder accepts the  
computed branch metrics and decodes the received signal. The non linear channel  
estimator can be fabricated using a Volterra kernel estimator or a lookup table estimator  
as illustrated at 1401 as illustrated at 1433 in Figure 14A or a look up table  
15 implementation as illustrated at 1433 in Figure 14B.

## 1 WHAT IS CLAIMED IS:

1. A method for modeling the behavior of a data channel the method comprising:

5 determining a sequence of data input to the data channel;  
using at least part of the sequence of data input to the data channel as an index to a channel model value;

sampling the data after it has passed through the channel to produce a sampled value;

10 comparing the channel model value with the sampled value; and  
adjusting the channel model value based on the results of the comparison between the channel model value and the sampled value.

2. A method as in claim 1 wherein determining a sequence of data input to the data channel comprises determining the last N bits input to the channel.

15 3. A method as in claim 2, where  $N = 5$ .

4. A method as in claim 1 wherein the sampling of the data after it has passed through the channel to produce a sampled value comprises producing a real number representing the sampled value.

20 5. A method as in claim 1, wherein adjusting the channel model value further comprises adjusting the channel model value according to an LMS (Least Means Squared) algorithm.

25 6. A method as in claim 1 wherein adjusting the channel model value further comprises adjusting the channel model value until it converges.

7. A method as in claim 6 further comprising converting the look up table into Volterra Kernels.

30 8. A method as in claim 7 further comprising converting the look up table into Volterra Kernels using a Hadamard transform.

35 9. A method as in claim 7 further comprising adjusting the Volterra Kernels based on the results of the comparison between the channel model value and the sampled value.

1           10. A method as in claim 9 further comprising eliminating the insignificant Volterra Kernels.

5           11. A method for modeling the behavior of a data channel the method comprising:  
determining a sequence of data input to the data channel;  
determining a Volterra Series representation of the channel;  
accepting at least part of the sequence of data input to the data into the Volterra series representation of the channel to produce a channel model value;  
10           sampling the data after it has passed through the channel to produce a sampled value;  
comparing the channel model value with the sampled value; and  
adjusting the channel model value based on the results of the comparison between the channel model value with the sampled value.

15           12. A method as in claim 11 wherein determining a Volterra Series representation of the channel comprises:  
accepting a most recent value of the sequence of data input to the data channel;  
accepting the most recent value of the sequence of data input to the data channel into a first FIR (Finite Impulse Response) filter;  
20           accepting a product of the most recent value of the sequence of data input to the data channel and a second most recent value of the sequence of data input to the data channel into a second FIR; and  
summing an output of the first FIR and output of the second FIR to form the channel model value.

25           13. A method as in claim 11 wherein determining a Volterra Series representation of the channel comprises:  
accepting a most recent value of the sequence of data input to the data channel;  
accepting the most recent value of the sequence of data input to the data channel into a first FIR filter;  
30           accepting a product of the most recent value of the sequence of data input to the data channel and the second most recent value of the sequence of data input to the data channel into a second FIR;  
accepting a product of the most recent value of the sequence of data input to the data channel and a third most recent value of the sequence of data input to the data channel into a third FIR; and  
35           summing an output of the first FIR and output of the second FIR and output of the

1        third FIR to form the channel model value.

14.    A method as in claim 11 wherein determining a Volterra Series representation of the channel comprises:

5        accepting a most recent value of the sequence of data input to the data channel;  
      accepting the most recent value of the sequence of data input to the data channel into a first FIR filter;

      accepting a product of the most recent value of the sequence of data input to the data channel and the second most recent value of the sequence of data input to the data channel into a second FIR;

10        accepting a product of the most recent value of the sequence of data input to the data channel and a third most recent value of the sequence of data input to the data channel into a third FIR;

      accepting a product, said product being the most recent value of the sequence of data input to the data channel and the two next most recent data input, into a fourth FIR; and

15        summing an output of the first FIR and output of the second FIR and output of the third FIR and output of the fourth FIR to form the channel model value.

20        15.    A method as in claim 11 wherein the difference between the channel model value and the output of the channel is used to update all the FIRs.

      16.    A method as in claim 12 wherein the difference between the channel model value and the output of the channel is used to update all the FIRs.

25        17.    A method as in claim 13 wherein the difference between the channel model value and the output of the channel is used to update all the FIRs.

      18.    A method as in claim 14 wherein the difference between the channel model value and the output of the channel is used to update all the FIRs.

30        19.    A method as in 15 wherein an LMS algorithm is used to update all the FIRs.

      20.    A method as in 16 wherein an LMS algorithm is used to update all the FIRs.

35        21.    A method as in 17 wherein an LMS algorithm is used to update all the FIRs.

1           22. A method as in 18 wherein an LMS algorithm is used to update all the FIRs.

          23. A method for equalizing an optical signal, modulated with a digital signal,  
received over an optical channel, the method comprising:  
5           converting the optical signal into an electrical signal;  
          summing the electrical signal with a correction signal;  
          providing the summed signal to a detector;  
          detecting the summed signal to produce decisions;  
          providing the decisions to a nonlinear channel estimator; and  
10           estimating the correction signal in the nonlinear channel estimator.

          24. The method of claim 23 wherein estimating the correction signal in the  
nonlinear estimator further comprises:  
          accepting the decisions;  
          predicting the inter-symbol interference of the channel in a nonlinear channel  
15          estimator; and  
          forming a correction signal from the predicted inter-symbol interference.

          25. The method of claim 24 wherein predicting the inter-symbol interference  
of the channel further comprises:  
20          providing the decisions to a plurality of Volterra Kernels; and  
          summing the output of the plurality Volterra Kernels to form a correction signal.

          26. The method of claim 25 further comprising:  
          comparing the predicted inter-symbol interference to inter-symbol interference in  
the electrical signal; and  
25          updating the Volterra Kernels based on the result.

          27. The method as in claim 26 wherein updating the Volterra Kernels  
comprises using a LMS (Least Means Squared) algorithm to update the Volterra  
Kernels.

30          28. The method of claim 24 wherein predicting the inter-symbol interference  
of the optical channel further comprises:  
          providing the data decisions as an address into a look up table;  
          outputting a value stored in the look up table as the predicted inter-symbol  
interference;  
35          comparing the predicted inter-symbol interference to the inter-symbol interference

1 in the electrical signal; and  
updating the value stored in the look up table based on the result.

29. The method as in claim 28 wherein updating the value stored in the look  
5 up table comprises using a LMS (Least Means Squared) algorithm.

30. An apparatus for equalizing a signal received over an optical channel, the  
apparatus comprising:

an input that accepts an optical signal;  
a converter that converts the optical signal into an electrical signal;  
10 a summation unit that sums the electrical signal with a correction signal;  
a detector that detects the summed signal to produce decisions; and  
a nonlinear channel estimator that estimates the correction signal.

31. The apparatus of claim 30 wherein the nonlinear estimator further  
15 comprises:

an input that accepts the decisions;  
an estimating circuit that predicts the inter-symbol interference of the channel;  
and  
an output that provides a correction signal from the estimated inter-symbol  
20 interference.

32. The apparatus of claim 31 wherein estimating circuit that estimates the  
intersymbol interference of the channel further comprises:

a plurality of Volterra kernels that accept the decisions and produce individual  
outputs; and  
25 a summation unit that sums the individual outputs of the plurality of Volterra  
Kernels to form a correction signal.

33. The apparatus of claim 32 further comprising:

a comparator for comparing the predicted inter-symbol interference to the inter-  
30 symbol interference in the electrical signal; and  
means for updating the Volterra kernels based on the result.

34. The apparatus as in claim 33 wherein the comparator that compares the  
predicted inter-symbol interference to the inter-symbol interference in the electrical  
35 signal includes a LMS (Least Means Squared) algorithm that compares the predicted  
inter-symbol interference to the inter-symbol interference in the electrical signal.

1           35. The apparatus of claim 31 wherein the estimating circuit that estimates the intersymbol interference further comprises:

a look up table which accepts the data decisions as an address into the look up table;

5           values of the predicted inter-symbol interference stored in the look up table;

a subtractor that subtracts the predicted inter-symbol interference from the electrical signal to produce a signal substantially free from intersymbol interference;

a second subtractor that subtracts the decision from the substantially inter-symbol interference free signal to produce an error;

10           and

means for updating the value stored in the look up table based on the error.

36. The apparatus as in claim 35 wherein comparing the comparator that compares the estimated inter-symbol interference to the inter-symbol interference in the electrical signal comprises a LMS (Least Means Squared) algorithm that compares the  
15           predicted inter-symbol interference to the inter-symbol interference in the electrical signal.

37. A method for decoding a signal received over an optical channel, the method comprising:

20           receiving a signal including linear and non linear components;

estimating, in a non linear channel estimator, the expected values of the received signal;

computing the branch metrics based on the expected values of the received signal;

25           providing the computed branch metrics to a Viterbi decoder; and

Viterbi decoding the received signal using the branch metrics provided to the Viterbi decoder.

38. The method of claim 37 wherein estimating, in a non linear channel estimator, the expected values of the received signal comprises:

30           providing the value of the received signal to a Volterra kernel estimator; and

computing the expected value sent based on the output of the Volterra kernel estimator.

39. The method of claim 37 wherein estimating, in a non linear channel estimator, the expected values of the received signal comprises:

35           providing the value of the received signal as an address to a look up table; and

1 looking up the stored value as the actual value transmitted .

40. An apparatus for decoding a signal received over an optical channel, the apparatus comprising:

5 a receiver for receiving a signal including linear and non linear components;

a non linear channel estimator that computes the expected values of the received signal;

a branch metrics computer for computing the branch metrics based on the expected values of the received signal;

10 a Viterbi decoder that accepts the computed branch metrics and

Viterbi decodes the received signal.

41. The apparatus of claim 40 wherein the non linear channel estimator that computes the expected values of the received signal comprises a Volterra kernel estimator that computes the expected value sent based on the output of the Volterra kernel estimator.

42. The apparatus of claim 40 wherein the non linear channel estimator that computes the expected values of the received signal comprises a look up table that uses the value of the received signal as an address to look up the stored value as the actual value transmitted .

43. A method for detecting digital data modulated on an optical signal and received over an optical channel, the method comprising:

converting the optical signal to an electrical signal;

25 converting the electrical signal to a multibit digital representation;

estimating distortion introduced in the optical signal by the optical channel;

compensating the multibit digital representation for the distortion; and

detecting the digital data from the compensated multibit digital representation.

44. A method as in claim 43 wherein estimating distortion introduced in the optical signal by the optical channel comprises estimating in a Volterra Kernel estimator the distortion introduced in the optical channel.

45. A method as in claim 43 wherein estimating distortion introduced in the optical signal by the optical channel comprises estimating in a lookup table estimator the distortion introduced in the optical channel.



1           46. An apparatus for detecting digital data modulated on an optical signal and  
received over an optical channel, the apparatus comprising:  
a converter for converting the optical signal to an electrical signal;  
an analog to digital converter that converts the electrical signal to a multibit digital  
5 representation;  
an estimator that estimates distortion introduced in the optical signal by the  
optical channel;  
a compensator that compensates the multibit digital representation for the  
distortion; and  
10 a detector that detects the digital data from the compensated multibit digital  
representation.

47. A method as in claim 45 wherein estimator that estimates distortion  
introduced in the optical signal comprises a Volterra Kernel estimator.

15 48. A method as in claim 45 wherein estimator that estimates distortion  
introduced in the optical signal comprises a lookup table estimator.

49. An apparatus as in claim 46 wherein the estimator that estimates distortion  
introduced in the optical signal comprises a Volterra Kernel estimator.

20 50. An apparatus as in claim 46 wherein estimator that estimates distortion  
introduced in the optical signal comprises a lookup table estimator.

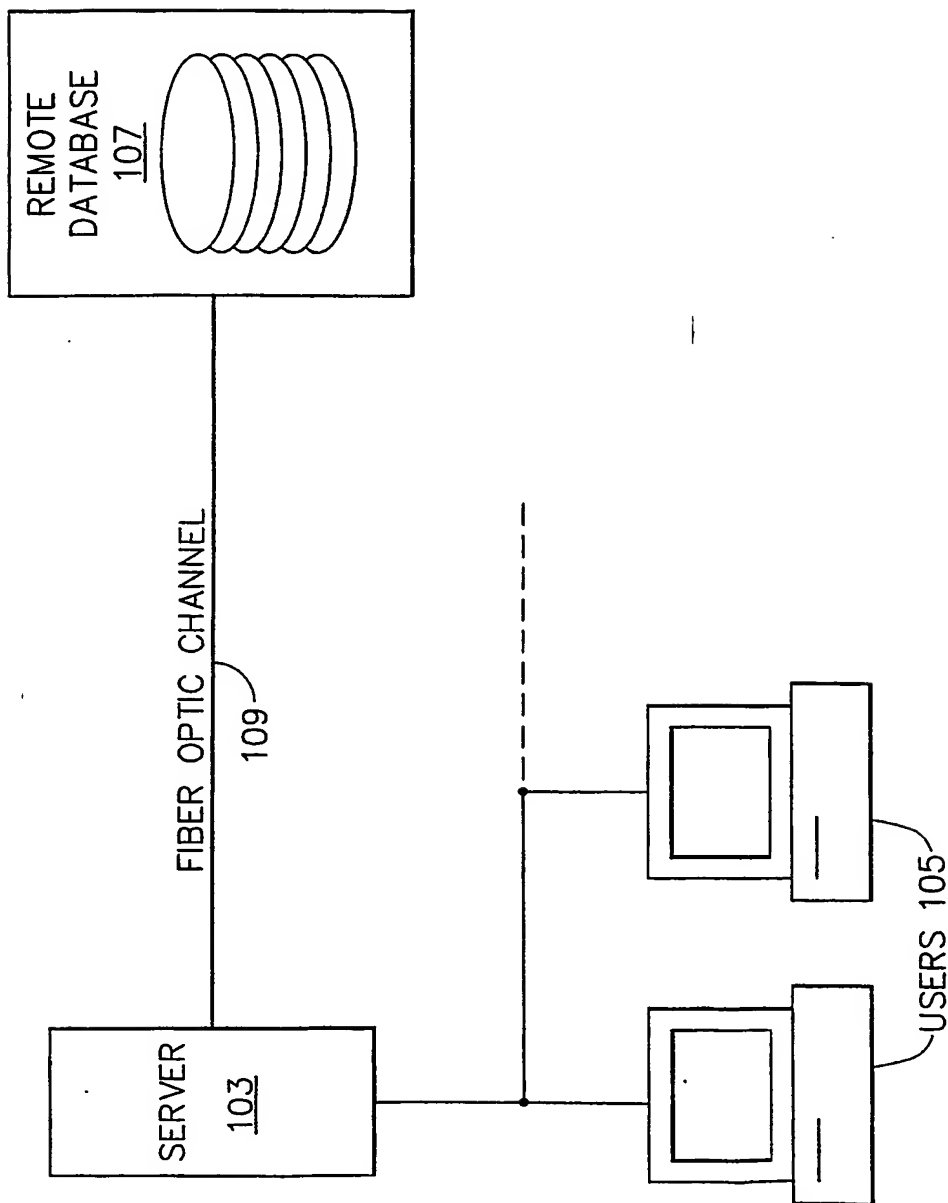


FIG. 1

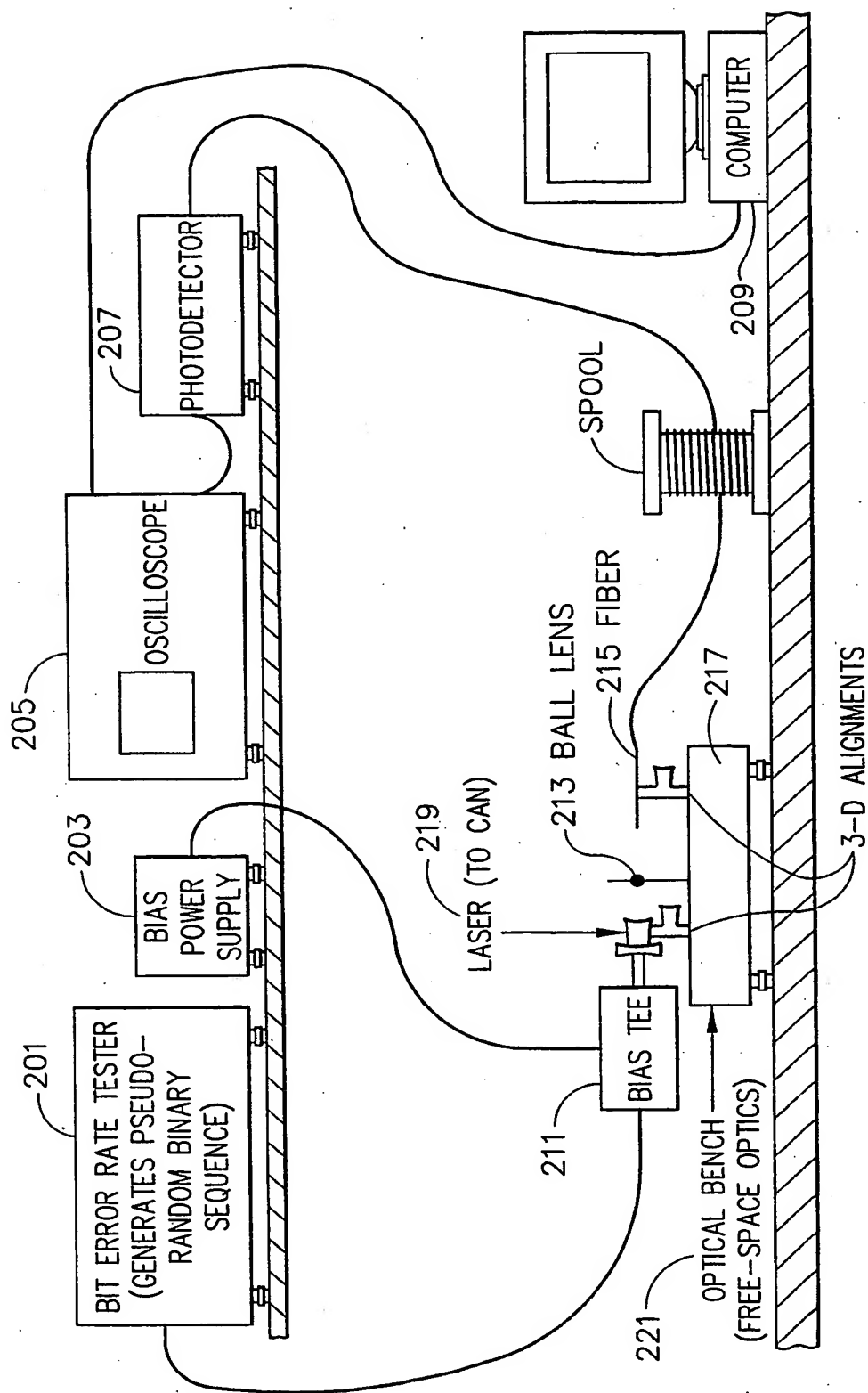


FIG. 2

FIBER	CORE DIAMETER [ $\mu\text{m}$ ]	LENGTH [m]	MANUFACTURER
F0	62.5	270	FUJIKURA
F1	50.0	1152	CORNING
F2	62.5	2234	CORNING
F3	50.0	2247	CORNING
F4	62.5	1151	CORNING
F5	50.0	540	CORNING

FIG. 3

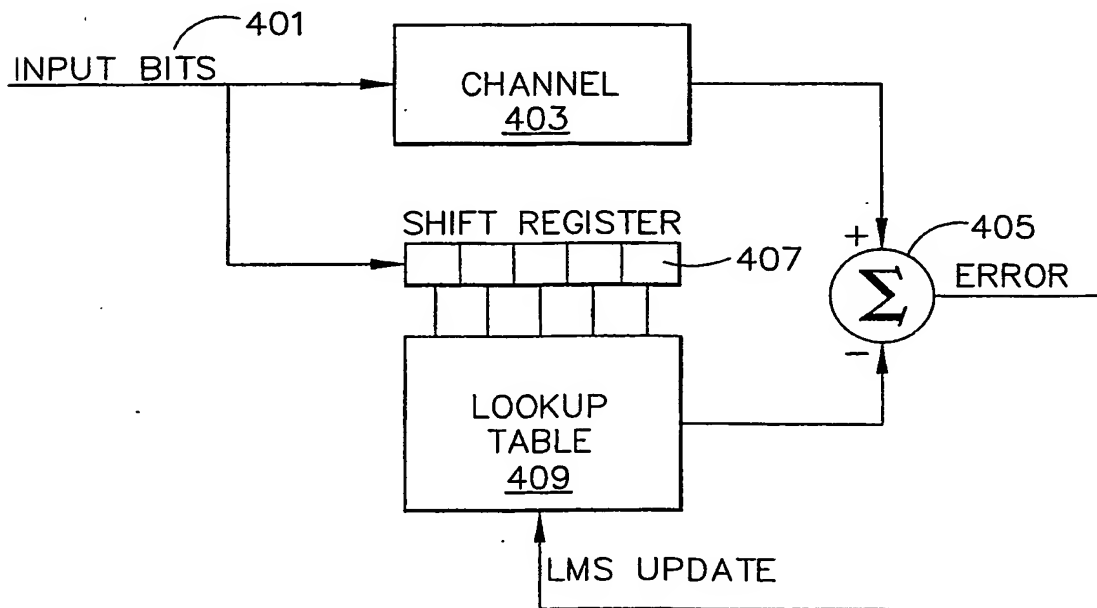
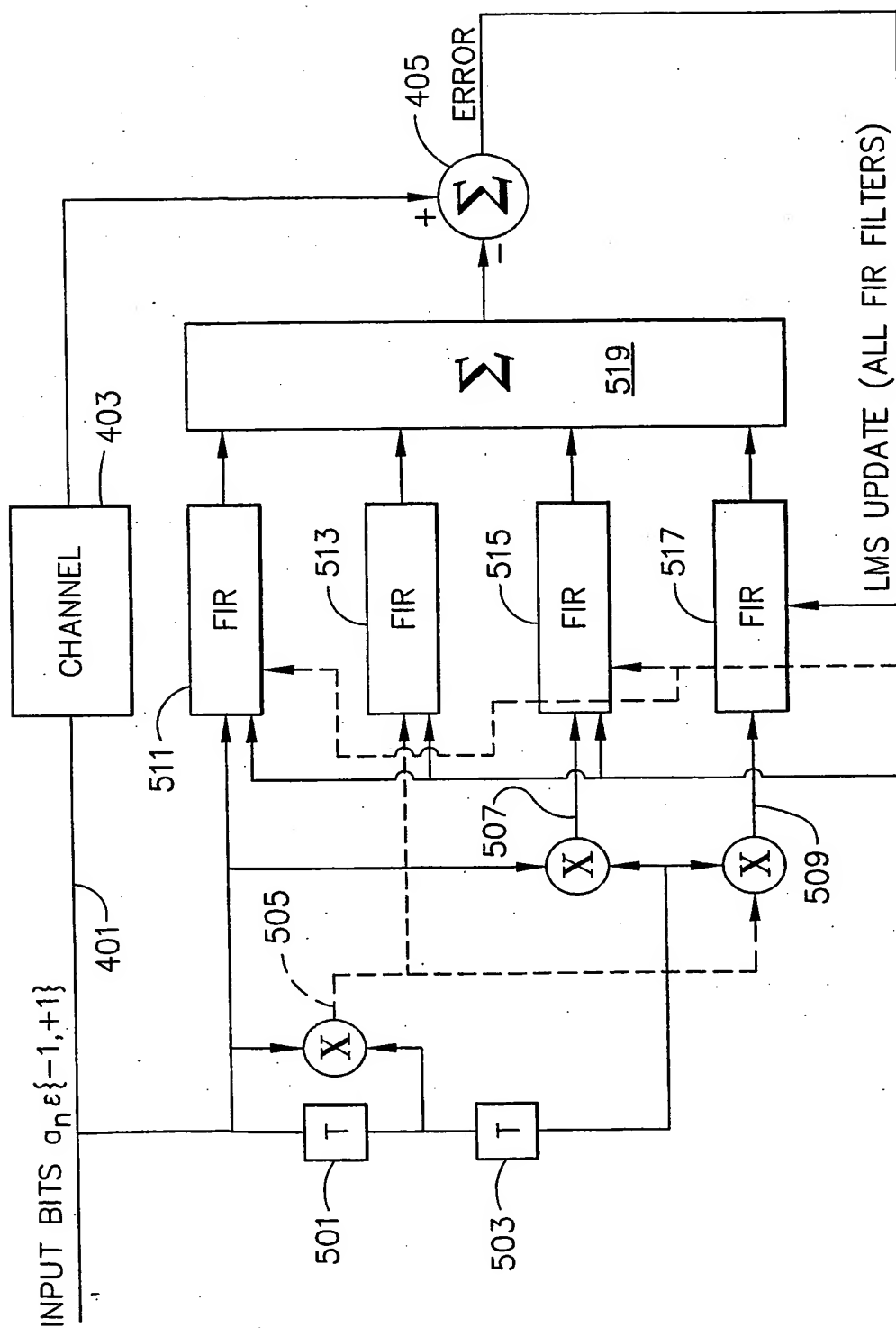


FIG. 4



NOTE: THIS SIMPLIFIED DIAGRAM SHOWS ONLY FOUR VOLTERRA KERNELS, AS WITH THE DATA TERMS  $a_n$ ,  $a_n a_{n-1}$ ,  $a_n a_{n-2}$ , AND  $a_n a_{n-1} a_{n-2}$

5  
6  
7

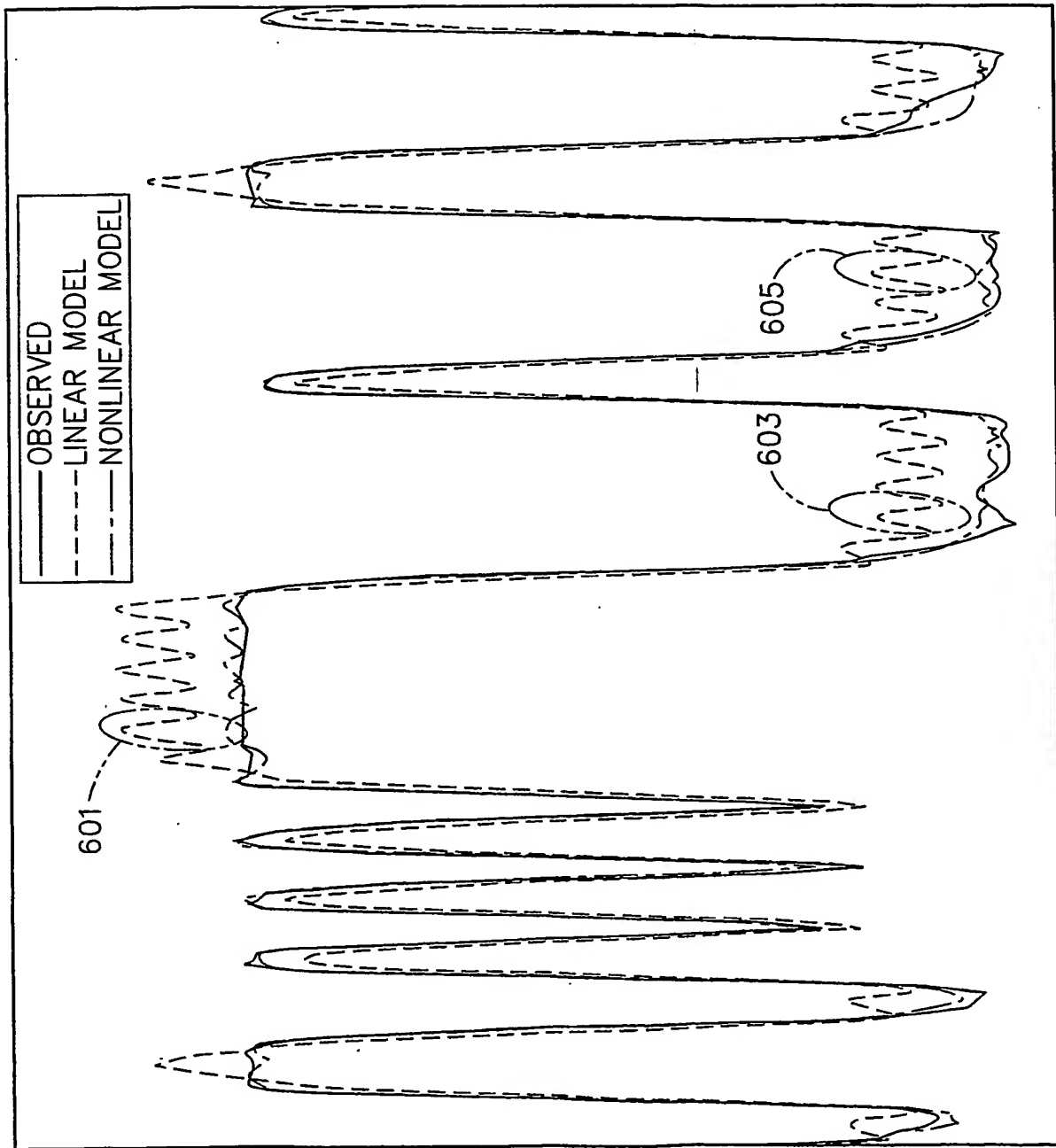


FIG. 6

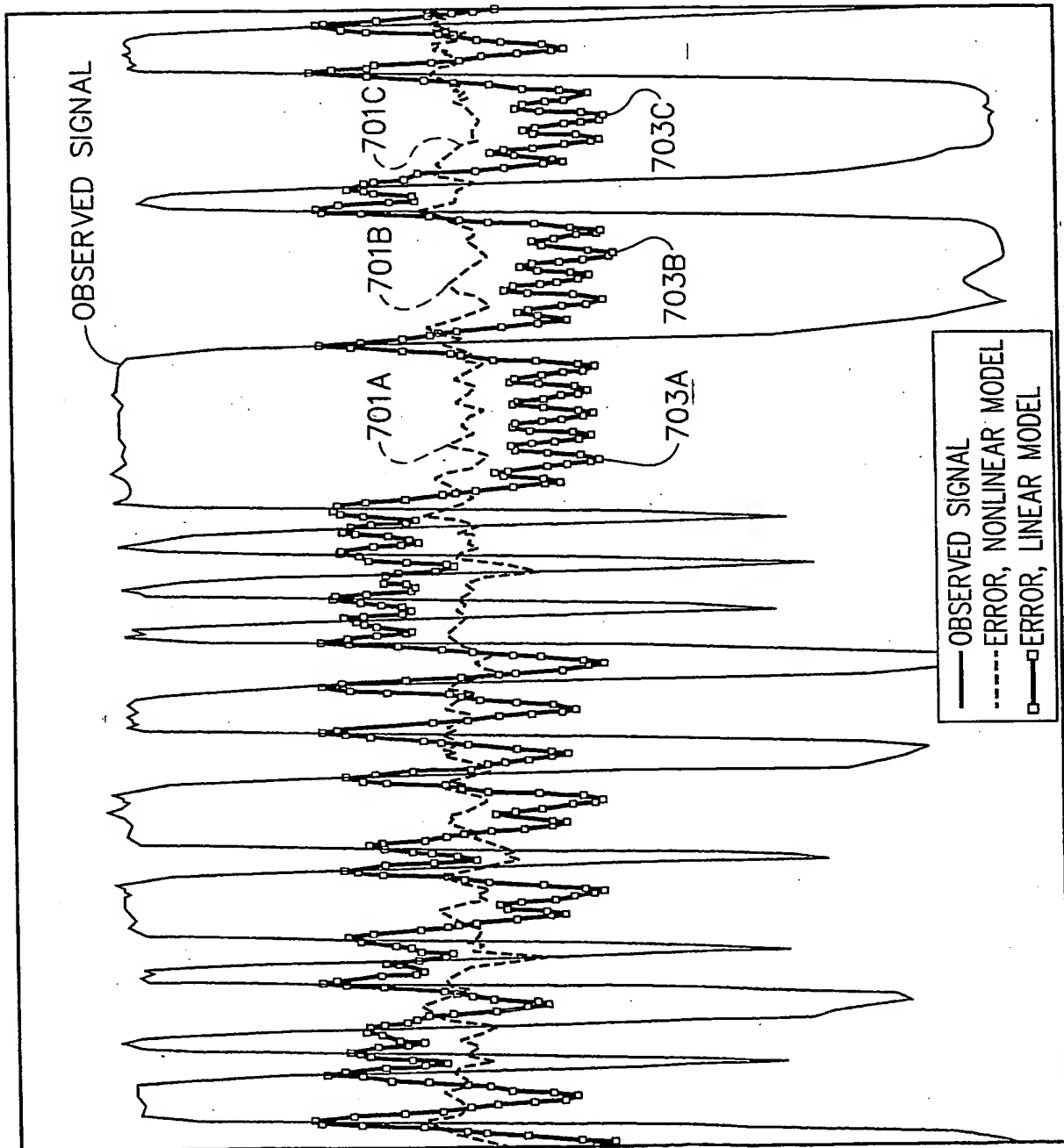


FIG. 7

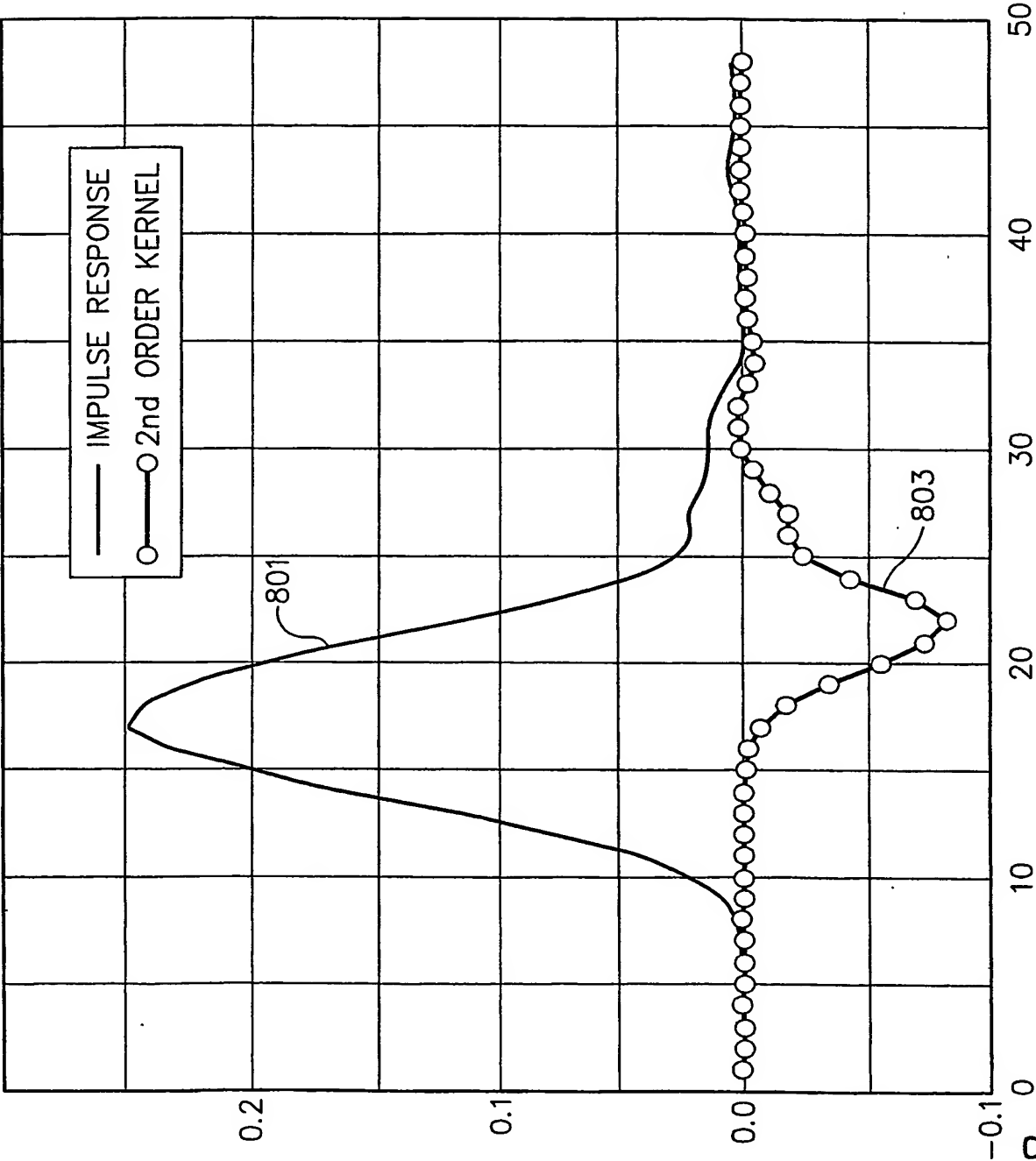


FIG. 8



FIBER	SNR [dB] (LINEAR MODEL)	SNR [dB] (NONLINEAR MODEL)
F0	12.8	23.2
F1	12.1	24.7
F2	13.4	24.9
F3	13.3	23.7
F4	12.4	23.8
F5	12.5	23.7

NOTE: SNR IS DEFINED AS  $10 \log_{10}(\text{SIGNAL POWER}/\text{ERROR POWER})$ , AND IT DOES NOT NECESSARILY COINCIDE WITH THE SLICER SNR OF A RECEIVER

FIG. 9

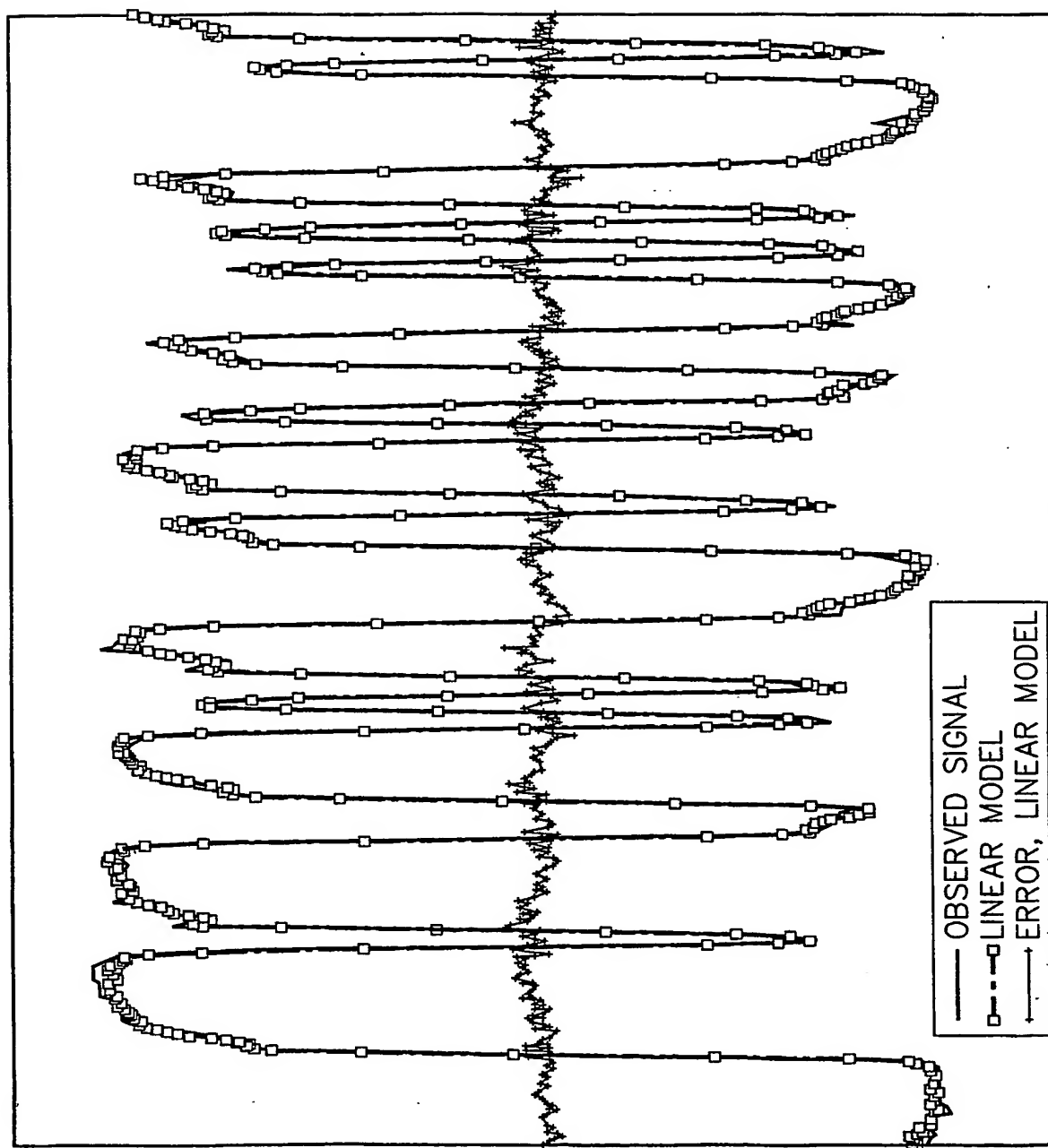
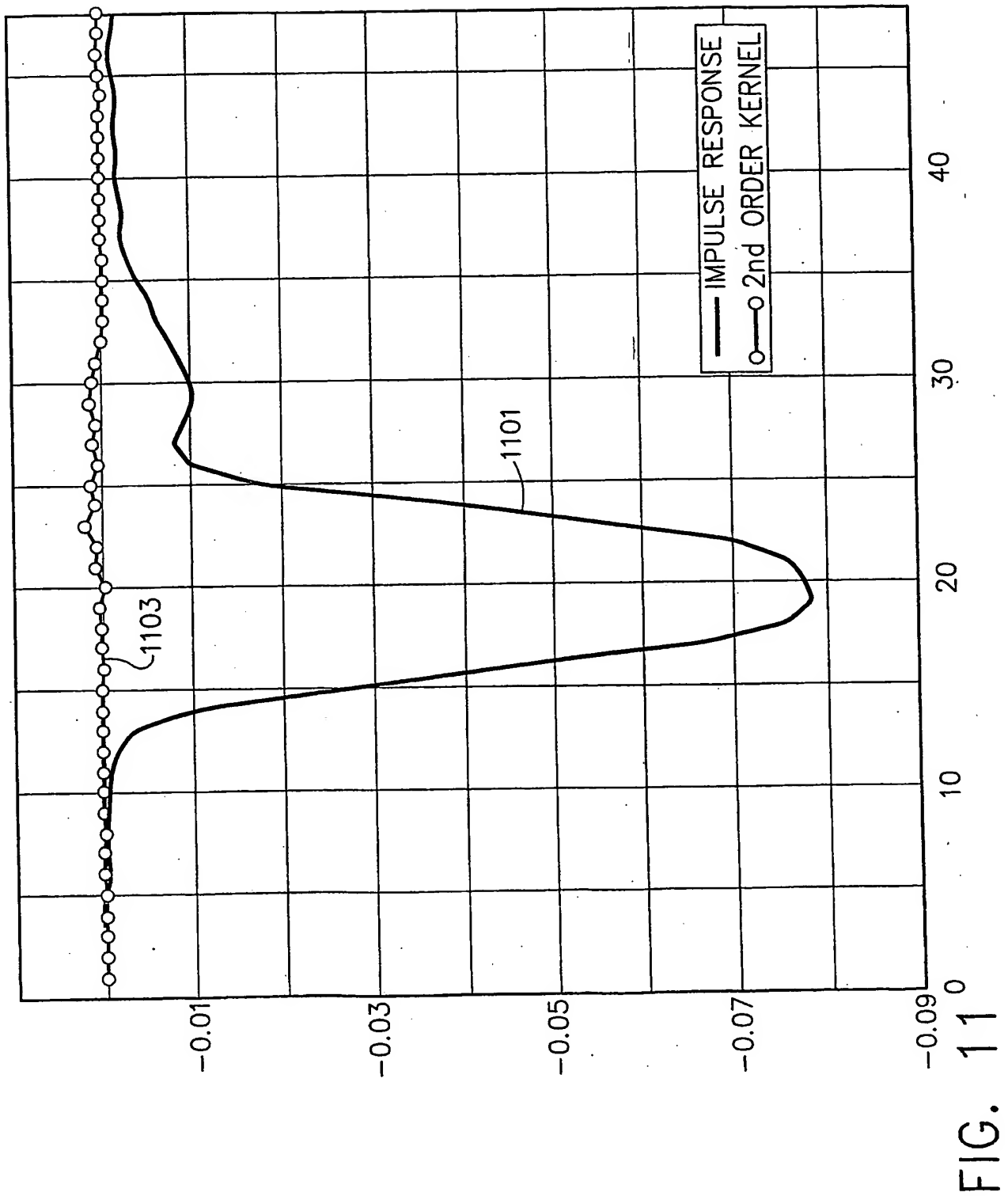


FIG. 10



FIBER	SNR [dB] (LINEAR MODEL)
F0	28.2
F1	26.6
F2	26.7
F3	27.4
F4	28.7
F5	28.2

NOTE: SNR IS DEFINED AS  $10 \log_{10}(\text{SIGNAL POWER}/\text{ERROR POWER})$ , AND IT DOES NOT NECESSARILY COINCIDE WITH THE SLICER SNR OF A RECEIVER

FIG. 12

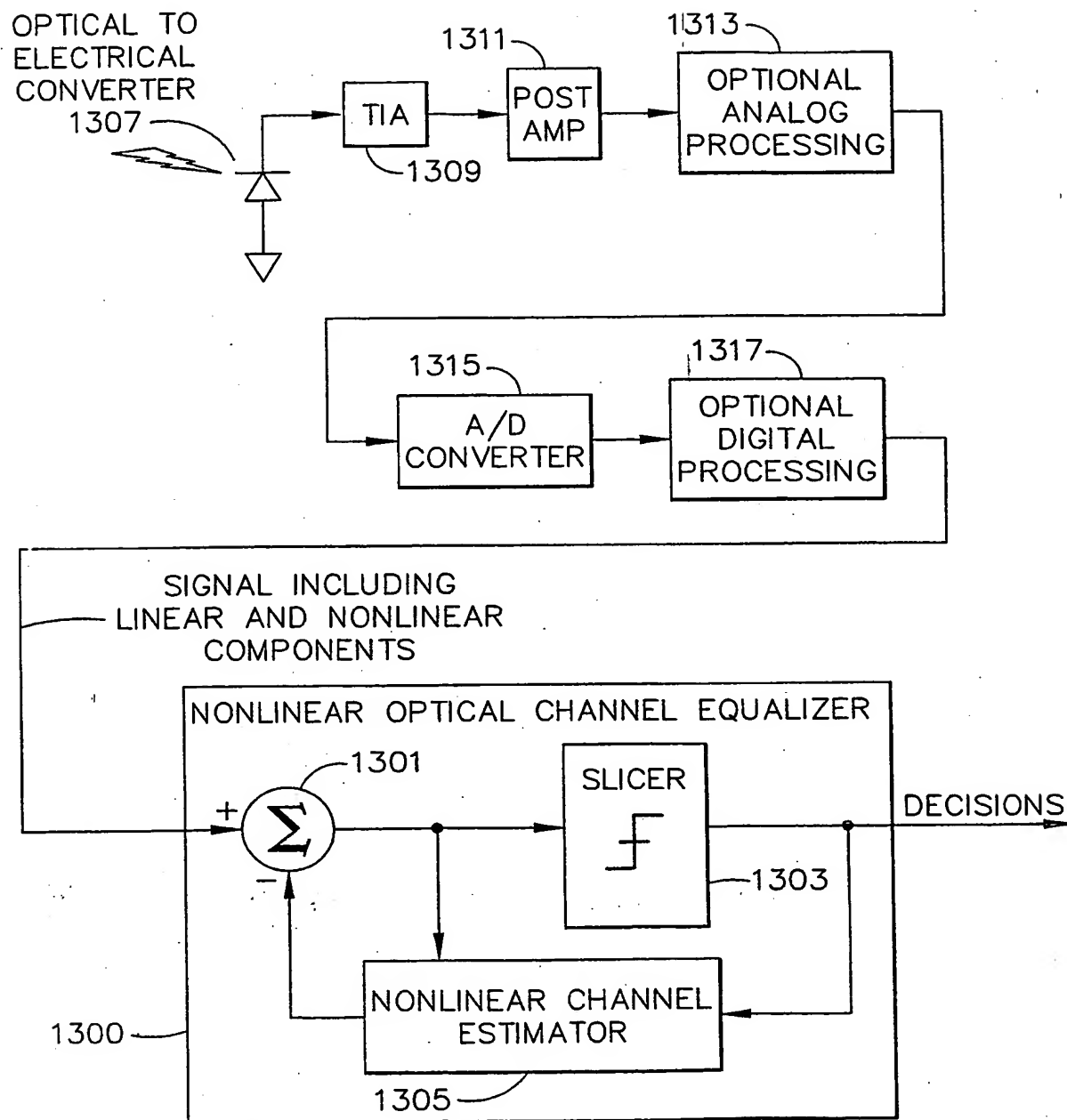


FIG. 13

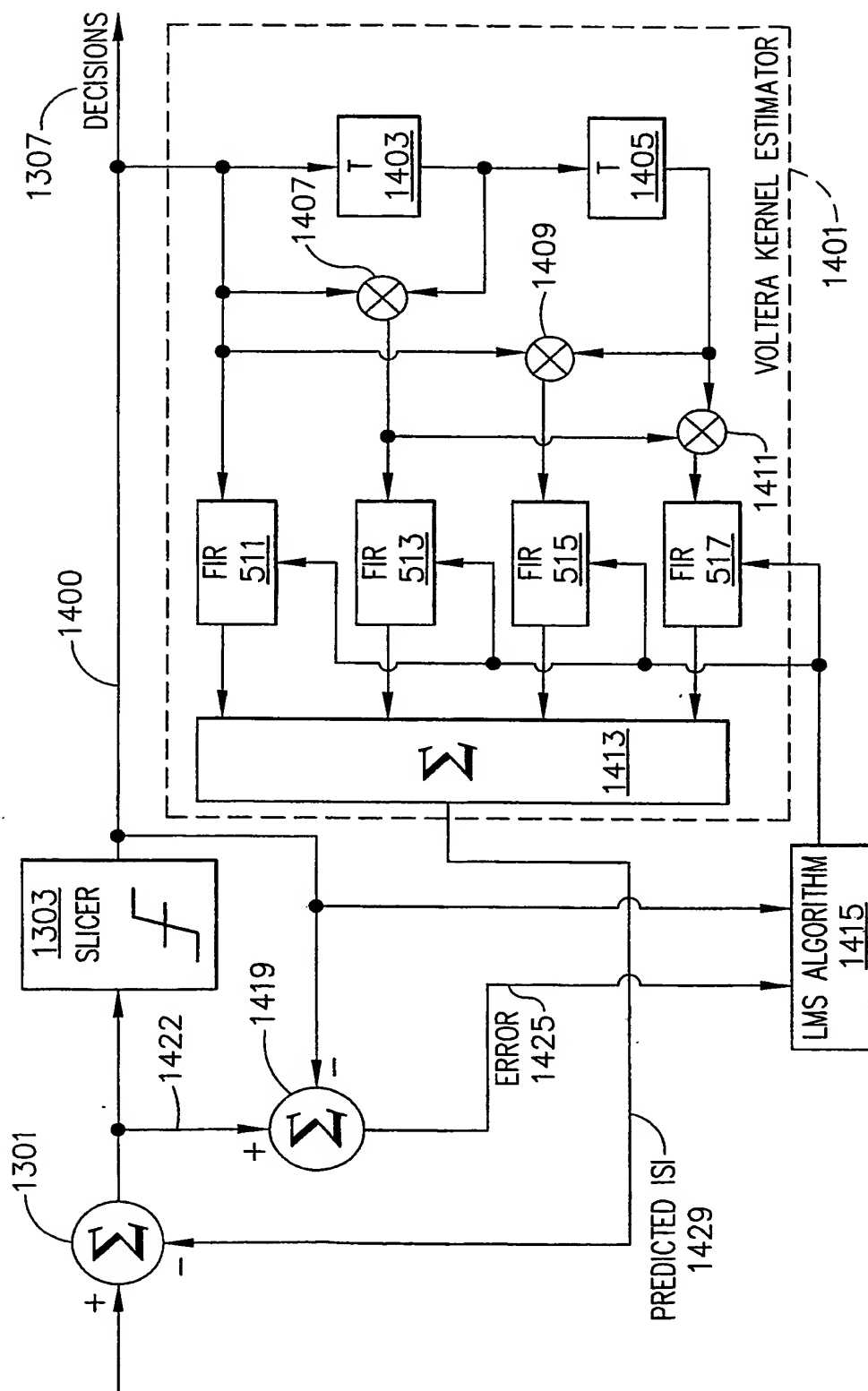


FIG. 14A

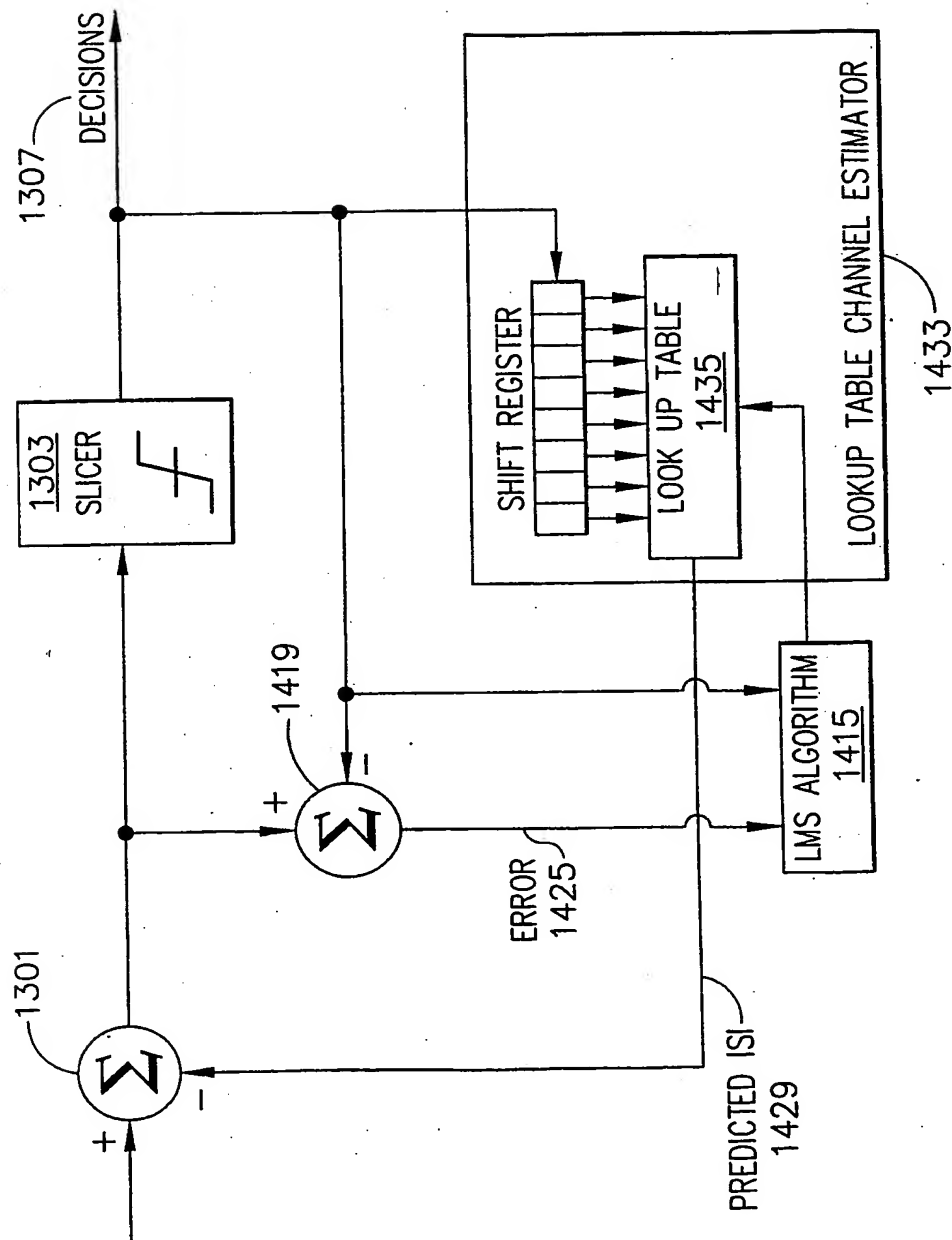


FIG. 14B

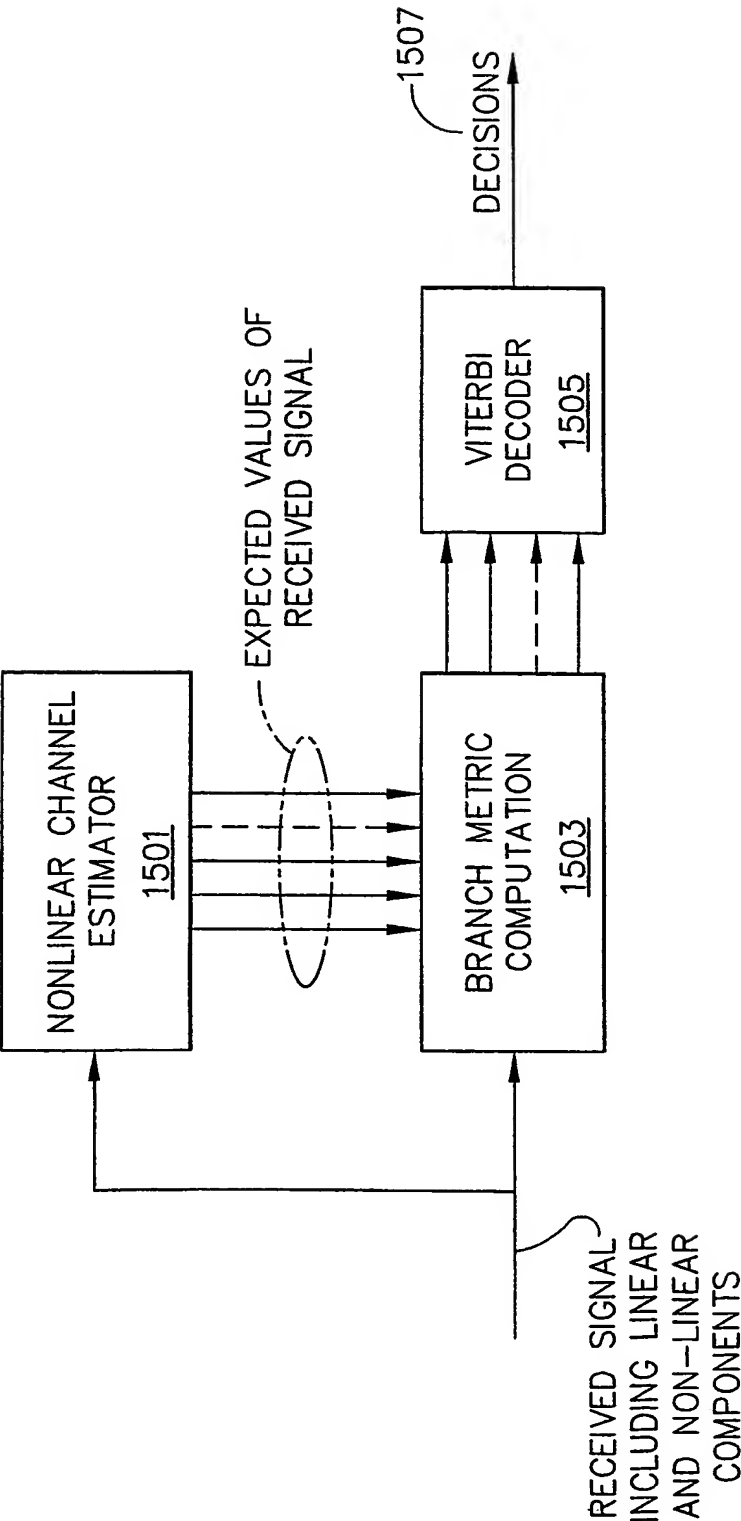


FIG. 15



## INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 01/43625

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 H04L25/02

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
IPC 7 H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC, COMPENDEX, IBM-TDB

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	BELLINI S ET AL: "Nonlinear cross talk cancellation for high density optical recording" CONFERENCE PROCEEDINGS ARTICLE , 1999, XP010373681 the whole document	1-29, 37-39, 43-45, 47,48
Y	---	30-36, 40-42, 46,49,50
Y	US 5 726 965 A (HAJJAR ROGER A ET AL) 10 March 1998 (1998-03-10) abstract; claim 1; figure 4 ---	30-36, 40-42, 46,49,50
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14 June 2002

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## INTERNATIONAL SEARCH REPORT

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## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	<p>THORMUNDSSON T ET AL: "Cancellation of nonlinear intersymbol interference in voiceband communication channels" COMMUNICATIONS, COMPUTERS AND SIGNAL PROCESSING, 1997. 10 YEARS PACRIM 1987-1997 - NETWORKING THE PACIFIC RIM. 1997 IEEE PACIFIC RIM CONFERENCE ON VICTORIA, BC, CANADA 20-22 AUG. 1997, NEW YORK, NY, USA, IEEE, US, 20 August 1997 (1997-08-20), pages 862-865, XP010245109 ISBN: 0-7803-3905-3 page 862, column 2, line 27 - line 60; figures 1,2 page 863, column 1, line 53 - line 62 page 863, column 2, line 56 -page 864, column 1, line 73 page 864, column 2, line 16 - line 39</p>	1-29, 37-39, 43-45, 47,48
X	<p>SANDS N P ET AL: "Non-linear identification on the digital magnetic recording channel" SIGNALS, SYSTEMS AND COMPUTERS, 1991. 1991 CONFERENCE RECORD OF THE TWENTY-FIFTH ASILOMAR CONFERENCE ON PACIFIC GROVE, CA, USA 4-6 NOV. 1991, LOS ALAMITOS, CA, USA, IEEE COMPUT. SOC, US, 4 November 1991 (1991-11-04), pages 6-10, XP010026261 ISBN: 0-8186-2470-1 abstract paragraph 'INTRODUCTION! paragraphs '02.6!', 'ADAPTIVE!', 'IDENTIFICATION! paragraph 'CONCLUSION!</p>	1-29, 37-39, 43-45, 47,48

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5726965	A	10-03-1998	NONE
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